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From: THE INSTITUTE OF RESPIRATORY PHYSIOLOGY,
UNIVERSITY OF OSLO, NORWAY
and THE INSTITUTE OF AVIATION MEDICINE,
ROYAL NORWEGIAN AIR FORCE, OSLO, NORWAY

RESPIRATORY RECOVERY FROM MUSCULAR EXERCISE OF SHORT DURATION

A functional study of healthy adults
in relation to age, sex and physical activity

By

K. LANGE ANDERSEN

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INTRODUCTION

The primary aim of this investigation has been to study the fitness for muscular work of healthy adult subjects. As the problem of assessing relevant data for this purpose is closely associated with development of proper testing procedures, this topic will be discussed first, only outlining the principal trends considered relevant to the problem.

Physiologically, the capacity for muscular work, this term taken in the broadest possible sense, depends upon the proper functioning of a large number of body organs, and their nervous and humoral regulation. However, as circulation and respiration evidently are of major importance, students of this field have mainly been concerned with measurements of these physiological mechanisms, and the following discussion will be limited to this aspect only. Although some well-defined isolated aspects concerning the function of the respiratory and circulatory organs have been long recognized, for instance the bellows function of the lungs, the functioning of the respiratory and circulatory system is integrated to such an extent that in this connection one hardly can separate the one system from the other. For instance the prime function of the lungs, the gas exchange between the atmosphere and the blood, involves the circulation through the lungs, which in turn depends on a proper functioning of the heart. Realizing this, it seems apparently of fundamental importance to use testing procedures giving a measure of the functioning of the combined cardio-respiratory system when dealing with problems of assessing data for determination of fitness for work. Having these data in hand it is reasonable to bring together more detailed information concerning the separate physiological mechanisms involved, in order to evaluate the limiting factors.

So far as this problem is concerned, numerous studies undertaken have shown that informative data cannot be obtained by studying the subjects at rest. Although interindividual differences exist in

young men for many physiological functions measured in the resting state which have been shown to have some relation to physical fitness (for references, see Karpovich 1953), the differences are arithmetically too small and the overlapping between fit and unfit persons too great to give any reliable measure of the physical working capacity.

It is by studying circulation and respiration in connection with performance of muscular exercise that one would expect to obtain informative and relevant data. This has also proved to be true in a number of investigations undertaken to elucidate this problem.

Evidently, standard exercise loads have to be performed in order to evaluate interindividual differences. It is perfectly obvious that the type of work selected for cardio-respiratory functional tests is important. This topic has been discussed in detail by Wahlund (1948). It appears that worktypes should be chosen which involve large muscle groups, and which give the least interindividual variability concerning the work efficiency.

Studies of circulation and respiration during performance of muscular exercise at a "steady state" level have proved to be only of limited value in assessing fitness for work, mainly because the differences between fitness and unfitness are arithmetically smaller the lower the metabolic rate (Brouha and Savage 1945). Ventilation efficiency (determined from measurement of ventilatory equivalent for O_2-intake) is of some value; however, great overlapping between fit and unfit subjects exists (Eskildsen 1945, Norris et al. 1955, Durnin and Miculicic 1956). By counting the heart rate during "steady state" work of different intensities and establishing the relationship between heart rate and workload, valuable information about circulatory efficiency for work can be obtained (Aastrand and Ryhming 1955, Ryhming 1954). However, evidence is available showing that this test is limited to use on young adult subjects only (Robinson 1938, Aastrand 1958; Andersen, unpublished data). *

Realizing that the living body can deliver energy by two different chemical processes, the aerobic and the anaerobic, there appear to be an aerobic and an anaerobic capacity for each individual, which can be determined by measuring the maximal oxygen intake during

* Since this has been written Asmussen and Hemmingsen (Scand. J. Clin. Lab. Invest. 10:67, 1958) have suggested a method of determining maximal oxygen intake from submaximal work experiments, which also purport to give valuable information about elderly subjects' physical working capacity.

work, and the maximal oxygen debt which can be built up during exercise stress.

Published data about maximal oxygen intake obtained during performance of muscular exercise have recently been reviewed by Aastrand (1956), and this method is in many circles considered to bring about the best overall measure of the circulatory and respiratory fitness for work. However, this method has apparently several disadvantages. First, it requires that the subjects are exercised extremely violently in order to obtain maximal values. Although this kind of exercise can be safely performed by young healthy adults, few, if any at all will take the risk of stressing elderly or diseased subjects to such an extent. This limits considerably the use of this testing procedure. Secondly, the experimental procedures are laborious, requiring at least three runs. Thirdly, it has been demonstrated that the peak oxygen intake depends on the type of work performed. Higher maximal values have been found on the same subject when skiing instead of running a treadmill (Aastrand 1952).

Very little is known about the capacity for anaerobic work. It is reported that the maximal values for O_2-debt in young men running to exhaustion is 7—14 liters (Asmussen et al. 1948). The "all out" treadmill run introduced by Cureton (1951), which has been applied to a large number of subjects, offers an opportunity to obtain valuable information concerning the capacity for anaerobic work. Unfortunately, Cureton has placed the emphasis on the gross total oxygen intake, which is a mixture of oxygen intake during the short exercise period and the recovery period. The determination of maximal oxygen debt implies similar disadvantages to those for determination of maximal oxygen intake, and is in addition to a great extent dependent on the willpower of the subjects.

Determination of the circulatory and respiratory recovery time following completion of a standard work task has been widely used for studying fitness for work based on the principle that quicker recovery means better fitness (for references see Karpovich 1953 and Cureton 1947). The majority of tests introduced have concerned the heart or respiratory rate. The recovery times for the pulmonary ventilation and respiratory gas exchange have only been studied by a few investigators (Hill et al. 1923-4, Simonsen 1926, Liebenov 1928, Hebestreit 1929, Berg 1947). These studies revealed that large interindividual differences exist, and evidence is brought together showing

that these are caused by variability in the combined cardio-pulmonary functioning.

Recently the respiratory recovery time has been introduced as a clinical routine test by Erikson (1952), using a testing procedure which can also be safely applied to very weak subjects, and this test has been adopted in the present study in order to investigate the fitness for muscular work of healthy, adult subjects.

STATEMENT OF THE PROBLEM

Although investigations of circulatory and respiratory fitness for work have been undertaken to a large extent since Atwater introduced physiological studies of man's capacity for physical work 70 years ago (referred to by Passmore and Durnin 1955), there still exist gaps in our knowledge. As far as the healthy population is concerned this is especially true for elderly subjects. A few studies of the effect of "steady state" exercise on respiration and circulation have been carried out on subjects over 50 years of age (Norris et al. 1955, Durnin and Miculicic 1956).

However, the workloads used by these authors were moderate, and the results are not very informative from a physical fitness point of view. Robinson (1938) conducted work experiments on males up to 90 years of age, and determined maximal values for oxygen intake. Definite age differences were observed. Similar results were recently found by I. Aastrand (1958), who studied Swedish workers up to the age of 64.

Except for a study conducted by Berg (1947) on 36 men ranging in age from 20 to 60 years, no experimental data are available showing the respiratory recovery time from a standard exercise load of elderly healthy subjects.

The beneficial influence of physical training on circulatory and respiratory fitness for work of young men has been evaluated by several authors (for references see Karpovich 1953). However, very little is known about the effects of physical training regimen upon elderly people.

The precise purpose of this work has been to investigate the respiratory and circulatory fitness for muscular work in healthy adults. The respiratory gas exchanges before, during and after performance of brief exercise loads were considered in a limited number of subjects with the main emphasis placed on determination of the time required to recover from the exercise stress. In addition the blood lactate and

the heart rate responses to the same workloads were studied together with determination of the bellows function of the lungs.

The experimental results have been related to age and sex and the influence of body size and physical activity has been considered.

METHODS AND EXPERIMENTAL PROCEDURES

Instrumentation

The spirometer. A spirometer originally constructed by Scholander (1937, 1940) for experimental investigations of the respiratory function in diving animals was used. This spirometer has been modified for work physiological studies on humans by Erikson et al. (1951). This apparatus records a continuous respiratory difference line (R. D. line), a continuous pulmonary ventilation curve, and gives the carbon-dioxide output for one-minute periods. Section of the tracings taken from a resting subject is shown in fig. 1. The accuracy of the CO_2-

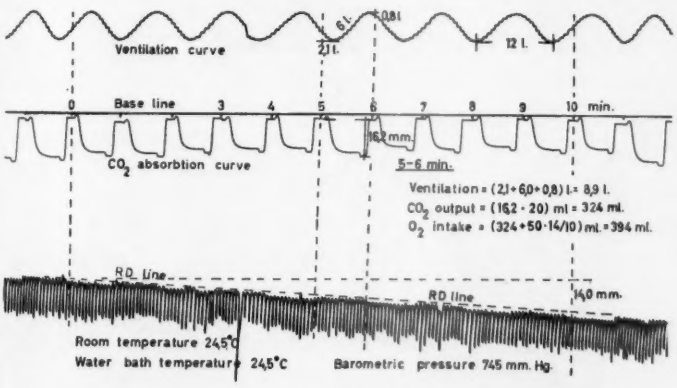

Fig. 1.

Section of spirometer tracings. The tracings show from above: Pulmonary ventilation, base line, CO_2-output per minute, spirometer curve with respiratory difference line (R. D. line) drawn through the expiratory ends of the respiration tracings. All volumes are recorded at ATPS. The water bath temperature (ambient temperature) has ranged between 20 and 22°C in the majority of the experiments.

output determined in periods of one minute is estimated to be within a range of ± 5 ml. The O_2-intake is calculated from the CO_2-

output and the slope of the R. D. line, the latter drawn on the spirometer tracing as shown in fig. 1. Although a calculation of O_2-intake in as short periods as one minute can be undertaken, a spirometer curve of at least 5—10 minutes duration is required if an exact determination of O_2-intake is desired.

The inspired air has the composition of atmospheric air. Spirometer pipes and tubes are of large dimensions to prevent noticeable resistance to the airflow.

The valve is constructed so that the opening pressure is minimized, and furnished with a diaphragm in the middle in order to reduce the dead space (Erikson and Rausand 1957).

The bicycle ergometer. A bicycle ergometer of the mechanical brake type was used. The resistance applied to the ergometer wheel was controlled by means of an arrangement similar to that advocated by Döbeln (1955). During the experiments the subjects were sitting in a comfortable chair with the ergometer wheel in the front (see fig. 2).

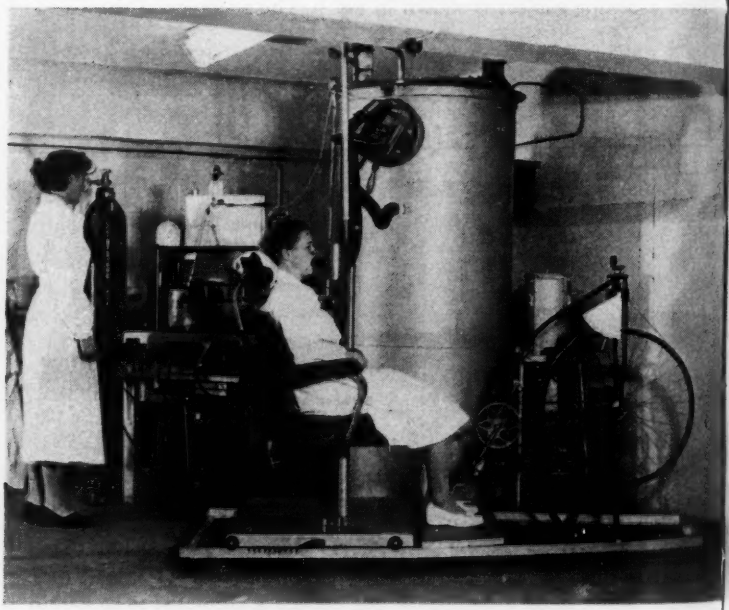

Fig. 2.
A subject connected to the spirometer.

This arrangement has several advantages over the conventional bicycle seat commonly employed for work physiological studies, and makes it possible to study the subject during exercise and a prolonged resting period without disconnecting from the spirometer and without moving the subject.

The tachy-cardiograph. The heart rate was continuously recorded with a tachy-cardiograph. By means of this machine the differences of the electrical voltages accompanying each heart beat were amplified electronically, and recorded on a Brush pen-recorder. Plate-electrodes were fastened to the skin by using adhesive tape, and the electrodes were greased with electrode paste or basic solutions of the usual commercial type.

Work experiments

Three different workloads were applied in the actual testing program: 500, 1000 and 1500 kg-m, performed in one minute. A constant pedalling rate (67 rpm.) was used in all experiments, the workload increased by increasing the resistance on the ergometer wheel. The subjects were paced to the correct pedalling rate by means of a speedometer connected to the ergometer wheel. The number of ergometer wheel-rotations were recorded in each experiment by having a conventional revolution counter attached to the wheel, and thus an exact calculation of the work performed could be undertaken in each experiment.

Experiments with the lowest workload were conducted on all subjects studied. In addition experiments using a workload of 1000 kg-m. in one minute were undertaken by females below 30 and males below 60 years of age. In males below 30 years of age an additional experiment using a workload of 1500 kg-m. in one minute was conducted.

Some of the oldest subjects were unable to pedal sufficiently fast, and in those cases the exercise time was increased until the correct number of ergometer wheel-rotations was reached. In none of the experiments did the exercise exceed 75 seconds. No correction for prolonged exercise time and reduced exercise load was undertaken.

Criteria for determination of the recovery time

The pre-exercise resting values for the pulmonary ventilation, O_2-intake and CO_2-output were determined as the average of a ten-

minute period. In most experiments a period of 5—10 minutes respiration in the spirometer was necessary in order to obtain stable values concerning pulmonary ventilation and CO_2-output, which was directly checked on the recording paper. This means that a 15—20 minutes pre-exercise spirometer tracing was recorded. In the period following completion of the bicycling the experiments were continued until at least a ten-minute period with stable values concerning the gas exchange was recorded.

How closely the pre- and post-exercise resting values for O_2-intake and CO_2-output agree is shown in figs. 3 and 4. The post-exercise resting value deviates in many experiments somewhat from the initial level; however, only in a few experiments do these deviations exceed a limit of ± 10 %.

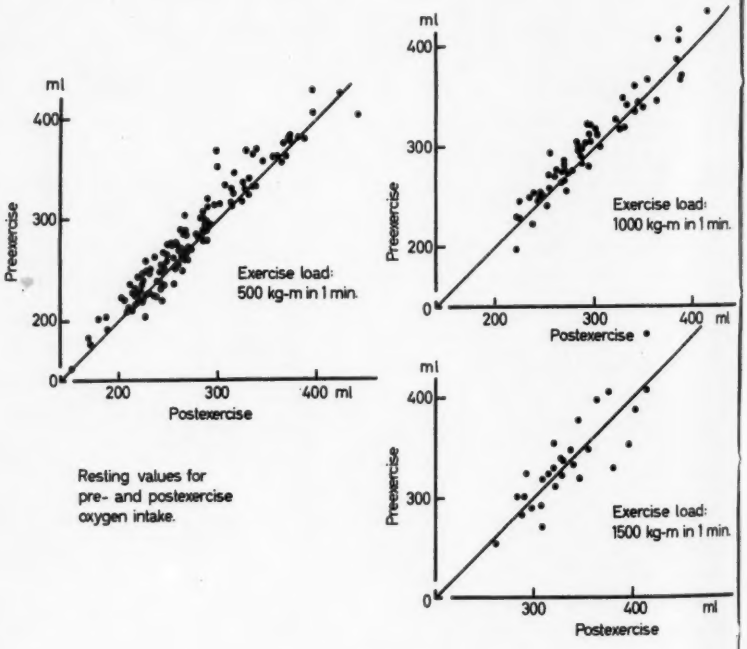

Fig. 3.

Relationship between resting value for pre- and postexercise O_2-intake. Diagonal line conforms with equal pre- and postexercise values.

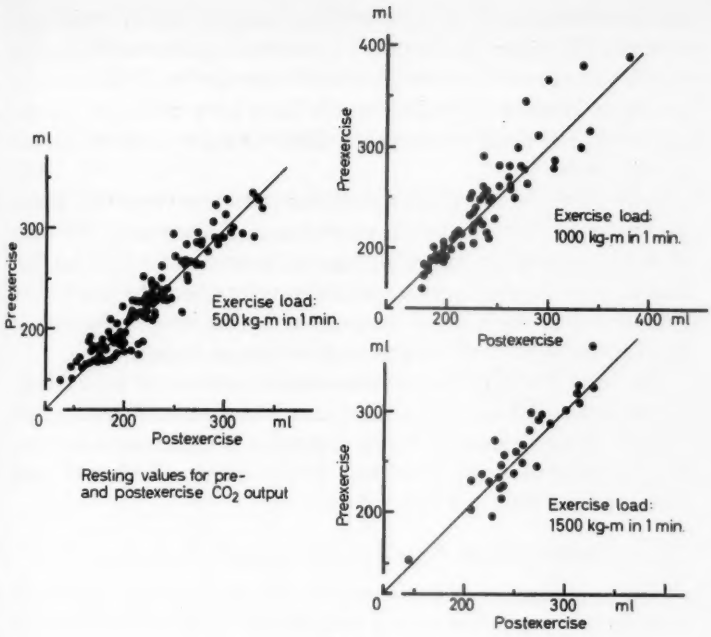

Fig. 4.

Relationship between resting value for pre- and postexercise CO_2-intake. Diagonal line conforms with equal values.

In determination of the recovery time for the gas exchange, the average of the pre- and post-exercise resting level was used as reference line. As it has been shown that the minute-to-minute variability for the O_2-intake as well as pulmonary ventilation and CO_2-output at rest may reach a limit of ± 10 % from this reference line, complete recovery was defined as that minute when the increased gas exchange following the exercise reached a value of 10 % above the reference line (Erikson, unpublished data).

As the curves for oxygen intake, pulmonary ventilation and carbon dioxide output in the period following completion of exercise are about exponential in shape, it is sometimes difficult to determine an exact recovery time. In order to minimize this difficulty it has been recommended to plot the data for the respiratory gas exchange on semilogarithmic graph paper, and thus fix the recovery time very

exactly (Simonsen 1926, Berg 1947). However, in this study considerable deviations from the pure logarithmic curve were frequently found. Consequently, this method for determination of the recovery time also involves difficulties which have been estimated by the author to be of about the same magnitude as the method introduced in this study.

Concerning the heart rate the minute-to-minute variability at rest is considerably less than for the gas exchange. Consequently, the limit of + 10 % above the resting level cannot be used as the limit for this. Instead complete recovery was set to that point where the heart curve following the completion of exercise reaches the level of the highest heart rates recorded in the pre- or post-exercise period.

The heart rate in the post-exercise period stabilized in some experiments on a higher level than before exercise for a considerable length of time. In such experiments it is impossible to determine a recovery time by using the criteria outlined. This problem will be dealt with later, in the chapter on Heart Rate.

Determination of the bellows function of the lungs

The vital capacity of the lungs and its subdivision in inspiratory capacity and expiratory reserve were measured with the spirometer described. The measurements were undertaken with the subjects in the semirecumbent position; the highest value of two readings was recorded and expressed at BTPS.

Maximal breathing capacity is defined as the maximal volume of gas that can be breathed per minute. The test was performed by using the spirometer described, the subjects being in the semirecumbent position. They were instructed to breath as deeply and rapidly as possible for a period of 20 seconds. Two determinations were undertaken, the highest value recorded and expressed at BTPS.

The terminology and the abbreviations recommended by American respiratory physiologists have been adopted (Pappenheimer 1950).

Determination of lactic acid in blood

The colorimetric method introduced by Barker and Summerson was used (1941). Lactic acid is oxidized to acetaldehyde by concentrated sulphuric acid. The acetaldehyde is determined colorimetrically by means of its reaction with p-hydroxidiphenyl in the presence of cupric ions.

Barker and Summerson recommended the removal of glucose with the copper-calcium treatment of Van Slyke after deproteinizing. Strøm (1949) found no significant difference in the determination of lactic acid, if the copper-calcium treatment was omitted, and his modification of the colorimetric method of Barker and Summerson was used in this study.

Recovery studies were undertaken, the results of which are given in table 1.

Table 1

Recovery studies of added lactic acid to blood

Sample	Blood lactate mg. %	Added lactate mg. pr. 100 ml.	Recovered	
			mg. pr. 100 ml.	%
1	25.0	20	19.0	95.0
2	15.5	100	91.5	91.5
3	15.5	50	51.5	103.0
4	15.5	25	21.5	86.0
5	12.9	5	4.9	98.0
6	6.7	10	10.1	101.0

Anthropometric measurements

The height of the subjects was measured to the nearest centimeter. The weight was determined on a usual clinical scale of the balanced type to the nearest kilogram. Body surface area was calculated according to the Du Bois formula (1916). Skinfold thickness was measured at three different points: on the abdomen above the iliac crest in the midaxillary line, on the back at the lower edge of the scapula, and midway on the upper arm on the posterior line.

A skinfold caliper of the type recommended by Keys and Brozek was used (1953). This caliper has circular jaws with a face surface of 25 mm^2, and a constant pressure of 20 gm/mm^2 was applied.

Statistical methods

Current statistical methods have been used for the calculation of arithmetical mean, standard deviation (st. dev.), and the coefficient of correlation (r). (Bradford Hill 1950.)

The significance of differences between mean values are analysed

according to students t-test on the assumption that the two means are drawn from the same population (Kemp 1942).

Following probability (P) levels of significance were used:

5 % level: P = 0.5 —0.01 : almost significant
1 % level: P = 0.01—0.001 : significant
0.1 % level: P = 0.001 : highly significant

SUBJECTS

Table 2 gives the number, age and sex distribution of subjects investigated. The oldest subject was a 96-year-old retired coachman, the youngest a 16-year-old male high-school student.

Table 2
Subjects: number, age and sex distribution

Age in years	Number	
	Men	Women
Below 20	3	1
20 — 29	31	12
30 — 39	11	4
40 — 49	8	2
50 — 59	22	3
60 — 69	10	1
70 — 79	13	8
80 and over	7	4
Total	105	35

Prior to the actual physiological testing procedures a routine clinical examination was undertaken of each subject, and all those having heart, lung or other major organic diseases were excluded. In most of the oldest subjects arterioscleroses of varying degree were diagnosed. Those with gross disorders are excluded from the material presented.

The subjects below 70 years of age were volunteers drawn from the population of Oslo. Of the 34 males below 30 years of age 12 were champion athletes, most of them engaged in skating and cross-country skiing. Some belonged to the world élite, being medal winners in the Olympic Games of 1952 or 1956. The athletes were studied during or just after the competitive season.

The other subjects, with one exception below 30 years of age, were mostly students from the College of Physical Education in Oslo (Statens Gymnastikkskole). Two of them were athletes, one 31 years of age. The rest were considered to be physically in better training than average for that age group. The other young men and women, although taken from professions involving mostly sedentary work, were not physically completely unconditioned as all of them were more or less fond of outdoor recreational activities which involve quite an amount of muscular exercise. Thirteen of the men between 55 and 70 years of age had for years engaged themselves very intensively in recreational sport activities, such as callisthenics, rowing, hunting, fishing, hiking in the woods and mountains every summer and winter. The 12 other men of this age group were selected from subjects who had lived sedentary lives for many years, involving no more exercise than walking to and from the streetcar and the exercise necessary in jobs of a sedentary type in business and industry.

Subjects above 70 years of age were selected from the healthy population belonging to the municipal old people's homes in Oslo,

Table 3
Subjects: height and weight
Men

Age in years	No.	Height in cm.		Weight in kg.	
		Mean	Range	Mean	Range
Below 30	31	178.3	164—191	72.2	62— 88
30 — 39	10	176.5	155—190	72.7	58— 90
40 — 49	8	177.6	162—192	79.5	65—108
50 — 59	19	172.3	164—183	74.9	60— 88
60 — 69	8	173.0	165—183	74.4	65— 85
70 — 79	13	167.5	160—176	63.1	51— 74
80 and over	7	163.3	154—168	67.0	61— 81

Women

Age in years	No.	Height in cm.		Weight in kg.	
		Mean	Range	Mean	Range
Below 30	13	163.3	158—175	60.0	51—68
30 — 69	9	162.6	149—181	60.9	45—74
70 and over	12	154.1	143—166	58.9	42—80

a prerequisite being that they were able to pedal the ergometer wheel at the desired rate. This involved that only the physically best part of the elderly population was studied. It may be of interest to mention that some of the old subjects were amazingly active with respect to muscular exercise, walking a couple of miles each day and taking hiking trips of up to 10 miles once a week.

In table 3 are listed data giving arithmetic mean and range for height and weight of the subjects studied. The means are compared with average values of a larger group of adult Norwegians published by Lindberg et al. (1956) (tables 4 and 5). Higher average values were found for the subjects of this material.

Table 4

Mean values for height (in cm.)

Comparison with data reported by Lindberg et al.

Age in years	Men		Women	
	Lindberg et al.	Own material	Lindberg et al.	Own material
20—29	176.2	178.3	164.0	166.3
30—39	175.3	176.5	163.0	162.6
40—49	173.6	177.6	161.8	
50—59	171.7	172.3	160.2	
60—69	170.5	173.0	159.0	

Table 5

Mean values for weight (in kg.)

Comparison with data reported by Lindberg et al.

Age in years	Men		Women	
	Lindberg et al.	Own material	Lindberg et al.	Own material
20—29	69.89	72.2	60.15	60.0
30—39	71.75	72.7	62.65	60.9
40—49	72.04	79.5	65.62	
50—59	72.31	74.9	67.03	
60—69	71.94	74.4	66.02	

In fig. 5 are shown values for abdominal skinfold thickness in relation to age. It is seen that the skinfold thickness on average increases with age. The same tendency was observed in the skinfold measured at the scapular region on the back and on the dorsal side of the upper arm; these data are not presented. Very few of the subjects were extremely obese; in general they were considered to be within the "normal" range.

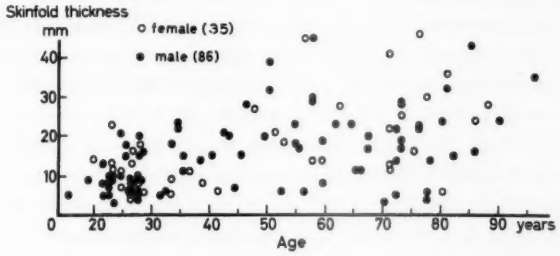

Fig. 5.

Thickness of abdominal skin fold in relation to age.

Table 6 shows the physical characteristics of sedentary and physically well-conditioned men. The athletes and the physically active elderly persons average more in height and weight and less as far as skinfold thickness is concerned. These data indicate that the amount of fat is relatively higher and the amount of muscle mass relatively larger in the athletes and in physically active compared to sedentary men.

Table 6

Physical characteristics of sedentary and physically well-trained men

Anthropometric measurements	20—29 years				55—69 years			
	Athletes (13)		Nonathletes (19)		Physically active (11)		Sedentary (9)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Height (cm)	182.0	172—191	175.7	164—189	175.9	165—183	172.2	167—183
Weight (kg)	76.9	63— 88	68.5	62— 83	77.1	65— 85	73.4	65— 88
Skinfold (mm)								
Abdomen	8	5— 13	10	3— 21	17	6— 30	22	11— 45
Back	8	7— 11	12	4— 21	12	8— 26	15	9— 28
Upper arm	8	5— 13	11	5— 19	10	3— 14	11	6— 18

O_2-INTAKE AND CO_2-OUTPUT

The respiratory gas exchange (O_2-intake and CO_2-output) remains elevated for a period of time after cessation of muscular exercise, showing that an oxygen debt and an excess content of metabolic produced carbon dioxide exist in the body after completion of work. (Benedict and Cathcart 1913, Hill et al. 1923-4.) Experimental evidence is available indicating that the oxygen debt is due to two different biochemical processes, one of these being the oxidation of lactic acid to CO_2 and H_2O and the glycogeneses in which the lactic acid is resynthesized to glycogen, a process which requires oxygen. The second process is not fully known; however, the hypothesis is advanced that the resynthesis of phosphocreatinine in the cells is the reaction which absorbs the energy developed in the process that occurs when the alactic debt is paid (Margaria et al. 1933).

When the work load is moderate for the subject performing the muscular exercise, only small amounts of lactic acid are formed, and the alactic debt is predominant, giving a rapid oxygen recovery, the oxygen intake being about an exponential function of time. After strenuous exercise leading to formation of considerable amounts of lactic acid, the recovery curve for oxygen intake has been shown to consist of two parts, an introductory sharp decrease, followed by a slow fall down to the initial level (Hill et al. 1923-4).

For moderate work the CO_2-output during the recovery period has been found to be an almost exponential function of time, although considerable deviations from the pure exponential curve have been demonstrated in many experiments reported in the literature (Simonsen 1926). The CO_2-output regains the pre-exercise resting level after the O_2-debt is paid off, this lag in CO_2-recovery being found by several authors (Hebestreit 1929, Berg 1947, Erikson 1957). Consequently, when determining respiratory recovery time from moderate muscular exercise, the time required for CO_2-output to reach resting level should be considered.

The anion-cation or "acid-base" balance of the circulating blood may influence the CO_2-output through the lungs. A lowering of pH leads to an excess outblowing of CO_2, and an increased pH is followed by a retention of CO_2. Whenever anion-cation balance is changed from the normal resting level, the CO_2-output through the lungs does not equal the metabolic CO_2. Such a change of the anion-cation balance takes place when exercise performed leads to formation of lactic acid (Turell and Robinson 1942). It has been shown experimentally that exercise resulting in a considerable increase of the blood lactate leads to an excess outblowing of CO_2 in the first part of the recovery, followed by subresting values later in the recovery, indicating a retention of CO_2, which might last for an hour or more after performance of very strenuous exercise (Hill et al. 1923-4).

When the excess CO_2-output is moderate and results in only a 2—4 % reduction of the CO_2 stores of the body, it has been shown that CO_2 is not retained within a reasonable period of time. In such experiments the elevated CO_2-output during recovery reaches the pre-exercise level and is not followed by subresting values (Bugge-Asperheim and Andersen 1957), and consequently, a CO_2-recovery time can be fixed. Also in those experiments it was found that CO_2-output recovered later than O_2-intake.

The recovery time for O_2-intake and CO_2-output following completion of a moderately brief standard exercise load shows large interindividual differences. Simonsen (1926), pioneering this field, demonstrated a longer O_2-recovery time in patients suffering from cardiac and pulmonary diseases than in healthy subjects. Berg (1947) studied the half time recovery constant for O_2-intake and CO_2-output following cessation of a short exercise load. His studies revealed that CO_2-output showed the largest interindividual variability while the variability between test - retest in a single individual was less than for O_2-intakes. These observations were confirmed by Erikson (1957).

In this study the respiratory gas exchange in connection with performance of brief standard exercise loads was investigated. The CO_2 recovery time was determined and the results were related to age and sex, and the influence of physical activity and body size was considered.

Results

Effect of aging

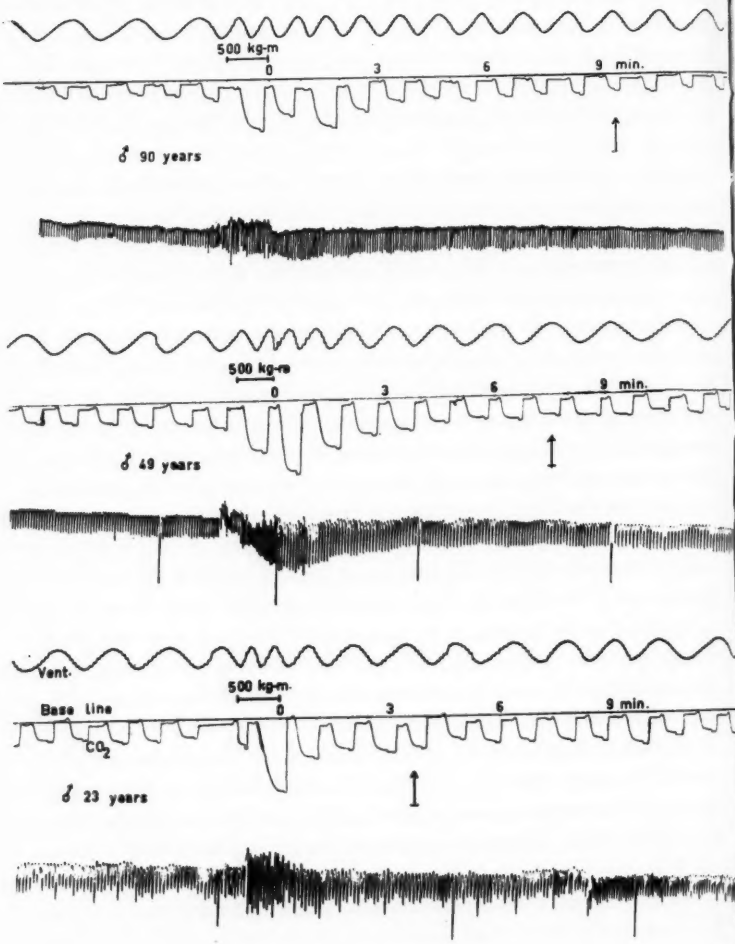

Fig. 6.

Section of spirometer curves taken from three male subjects. CO_2-recovery times are marked with arrows.

Fig. 6 shows sections of spirometer curves from three male subjects, aged 23, 49, and 90 years, each representing about the average for the

age group to which they belonged, concerning respiratory response to the exercise load. From the spirometer tracings the O_2-intake, CO_2-output and R. Q. have been calculated; the results from the oldest and youngest subjects are shown in figs. 7 a and b together with simultaneous figures for blood lactate.

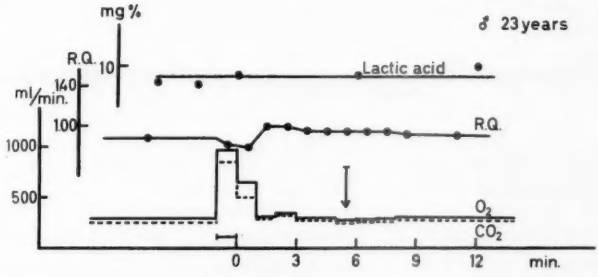

Fig. 7 a.

O_2-intake, CO_2-output (ATPS), R.Q. and blood lactate response to performance of 500 kg-m in one minute. CO_2-recovery time is marked with an arrow.

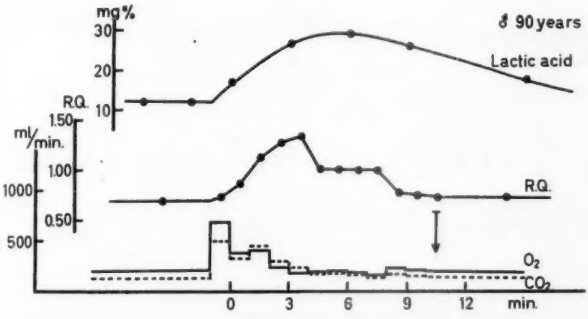

Fig. 7 b.

O_2-intake, CO_2-output (ATPS), R.Q. and lactic acid response to 500 kg-m, performed in one minute. CO_2-recovery time is marked with an arrow.

Age differences are clearly demonstrated in the figures. The respiratory gas exchange adapted to and recovered from the exercise stress at a much slower rate in the old compared to the young subjects.

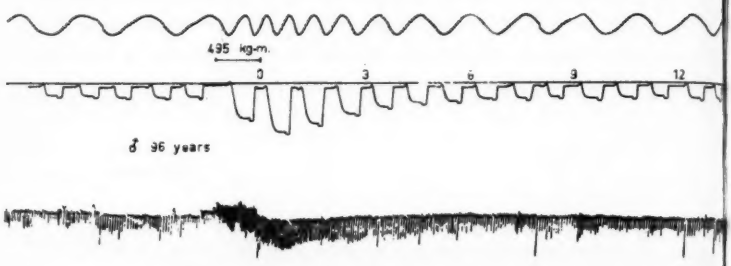

Fig. 8.

Section of spirometer curve taken from the experiment conducted on the oldest subject investigated. CO_2-recovery time was 14 minutes.

Fig. 8 shows sections of spirometer tracings from the oldest subject investigated, a 96-year-old retired coachman. His CO_2-recovery time was 14 minutes.

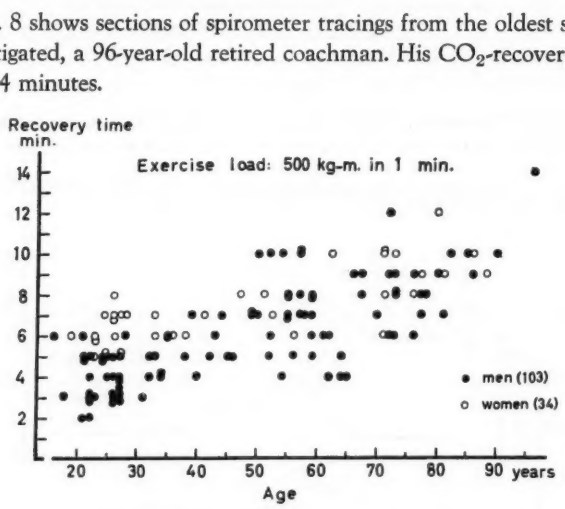

Fig. 9.

CO_2-recovery time in relation to age.

In fig. 9 the CO_2-recovery time has been plotted against age. Age differences are clearly shown in the figure.

Table 7 gives statistical data for the CO_2-recovery time in men. The subjects have been separated into four age groups. The difference between means of youngest and oldest age groups is statistically highly significant.

Table 7
CO_2-recovery time (in minutes)
following performance of 500 kg-m. in 1 minute
Men

Age in years	No.	Mean	St.dev.	Range
Below 30	33	3.85	1.18	2— 6
30—49	19	5.26	1.19	4— 7
50—69	31	7.03	1.96	4—10
70 and over	20	8.65	1.96	6—14
Total	103	6.00	2.40	2—14

Fig. 10 shows sections of spirometer curves from experiments where a workload of 1000 kg-m. in one minute was used. The calculated values for O_2-intake, CO_2-output and R.Q. are shown in fig. 11. Similar age differences to those observed for 500 kg-m. were found.

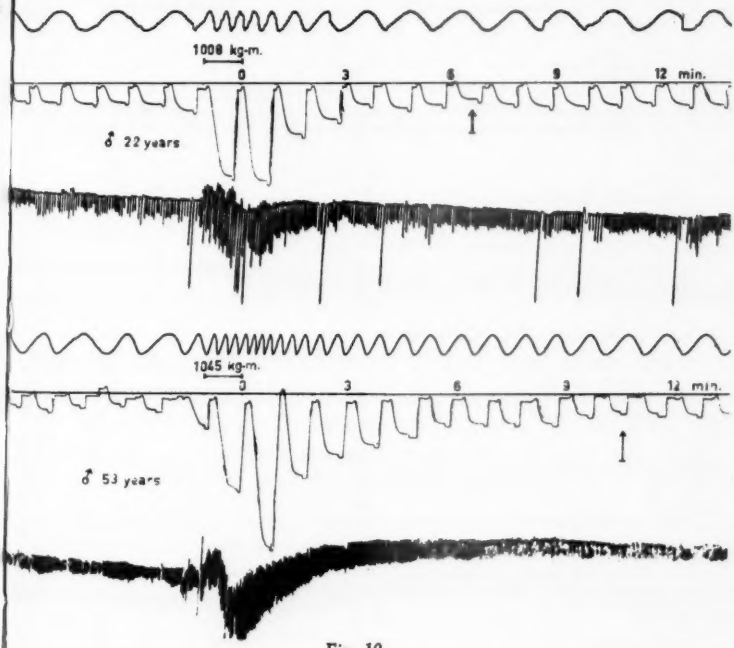

Fig. 10.
Sections of spirometer curves. Performance of 1000 kg-m in one minute by two male subjects, age 22 and 53 years. CO_2-recovery times are marked with arrows.

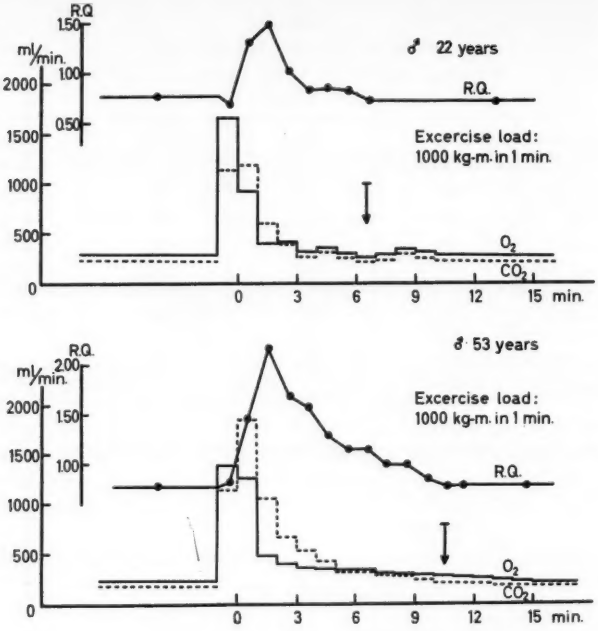

Fig. 11.

O_2-intake, CO_2-output (ATPS) and R.Q. response to performance of 1000 kg-m in one minute. CO_2-recovery times are marked with arrows.

A considerable elevation of the R.D. line took place on the curve from the oldest man, which indicated an elevated blood lactate. This problem is discussed later.

The results concerning CO_2-recovery time for all the 1000 kg-m. experiments are shown in fig. 12, while table 8 gives statistical data.

Table 8

CO_2-recovery time (in minutes)
following performance of 1000 kg-m. in 1 minute
Men

Age in years	No.	Mean	St.dev.	Range
Below 30	30	7.03	1.35	5—10
30—49	14	9.79	2.52	5—13
50 and over	12	11.17	2.28	8—15
Total	56	8.61	2.53	5—15

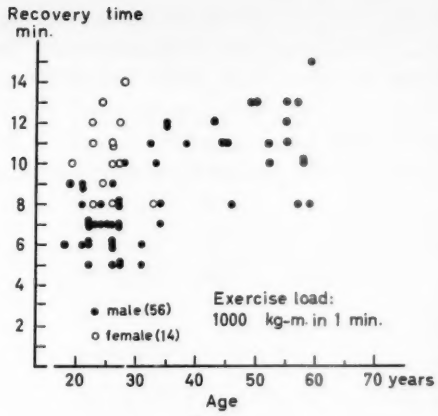

Fig. 12.
CO_2-recovery time in relation to age.

Sex differences

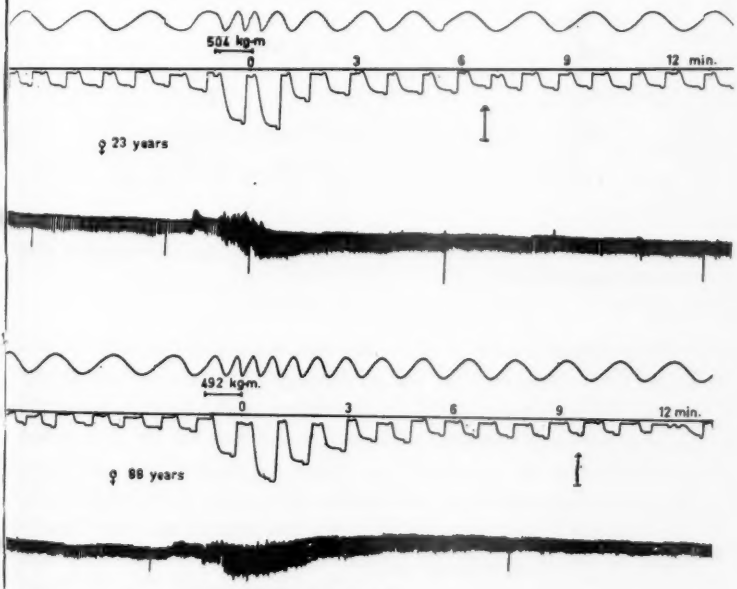

Fig. 13.
Sections of spirometer curves taken from two women, age 23 and 88 years. CO_2-recovery times are marked with arrows.

Fig. 13 shows sections of spirometer curves from experiments on females working at a load of 500 kg-m. in one minute. The 23-year-old woman's respiratory response was about average for that age. The 88-year-old woman was the oldest female tested. Her CO_2-recovery time was nine minutes, and an elevation of the R. D. line took place in the post-exercise period, indicating increased blood lactate.

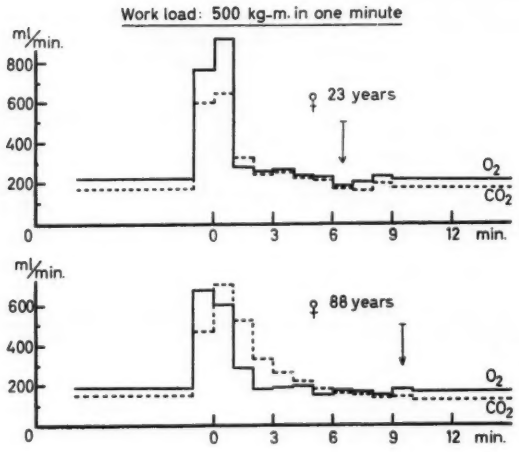

Fig. 14.
O_2-intake and CO_2-output (ATPS) response to exercise. CO_2-recovery time is marked with an arrow.

From figures 9 and 12 it is seen that women on average have a longer CO_2-recovery than males, although considerable overlapping exists. The differences between the means of the totals were found to be statistically significant. The same was true for the differences between mean values of subjects below 30 years of age, while the differences between means for higher age groups were insignificant. The number of women above 30 years investigated was small and it might be that a statistically significant difference would have been found if a larger number of women had been tested. The difference between nonathletes and women below 30 years of age is also statistically significant.

Table 9

CO_2-recovery time (in minutes)
following performance of 500 kg-m. in 1 minute
Women

Age in years	No.	Mean	St.dev.	Range
Below 30	13	6.31	0.95	5— 8
30—49	6	7.00	—	6— 8
50—69	4	7.75	—	6—10
70 and over	11	9.18	1.59	6—12
Total	34	7.53	1.73	5—12

The effect of physical activity

Some marked differences were observed between athletes and non-athletes in respiratory response to a standard exercise load. These differences are demonstrated in figs. 15 and 16.

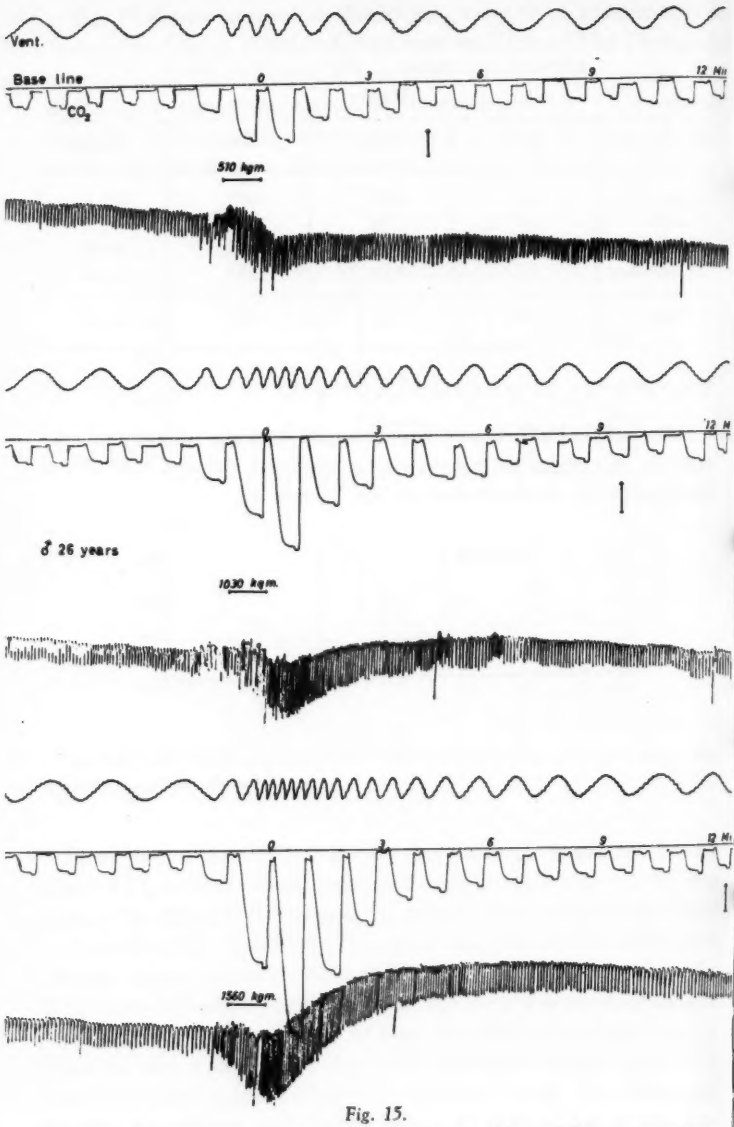

Fig. 15.

Sections of spirometer curves taken from a nonathlete. CO_2-recovery times are marked with arrows.

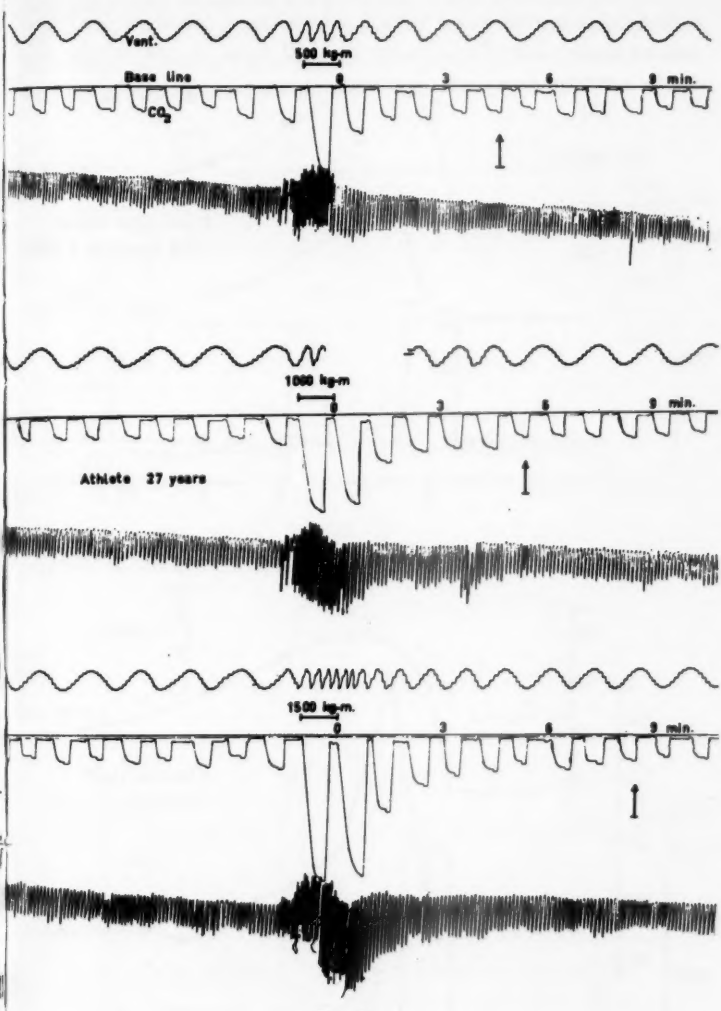

Fig. 16.

Sections of spirometer curves taken from an athlete. CO_2-recovery times are marked with arrows.

After work of 1500 kg-m. in one minute a considerable elevation of the R.D. line took place in the nonathlete during recovery, indi-

cating an increased blood lactate, which was verified by the blood studies undertaken. Performance of 1000 kg-m. in one minute also

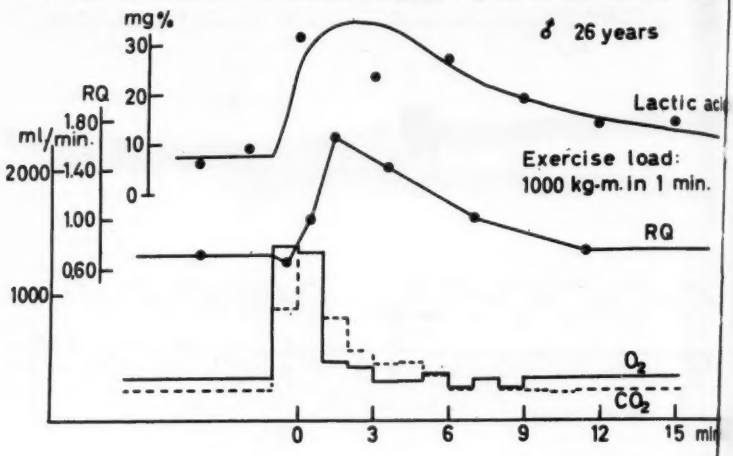

Fig. 17 a.
O_2-intake, CO_2-output (ATPS), R.Q. and blood lactate response to 1000 kg-m.

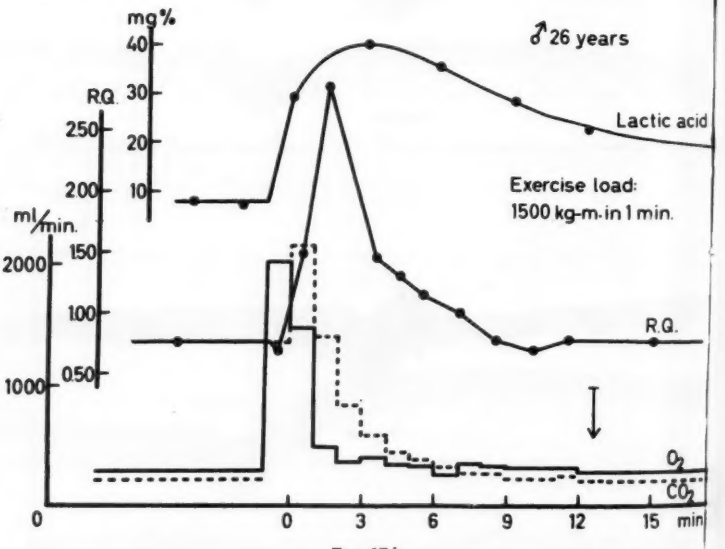

Fig. 17 b.
O_2-intake, CO_2-output (ATPS), R.Q. and blood lactate response to 1500 kg-m.

resulted in an elevation of the R.D. line. These exercise loads did not elevate the R.D. line on the spirometer curves of the athlete. The calculated values for O_2-intake, CO_2-output, R.Q. and corresponding values for blood lactate are shown in figs. 17 a and b and 18 a and b.

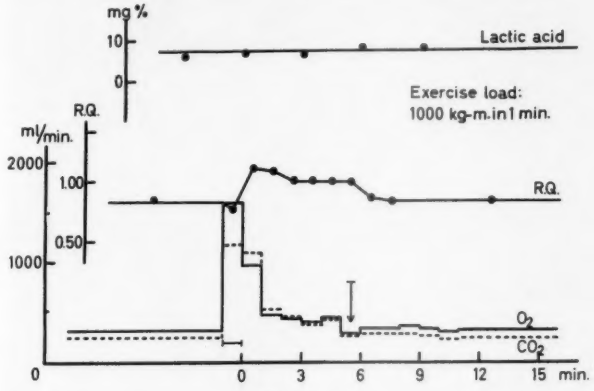

Fig. 18 a.
O_2-intake, CO_2-output (ATPS), R.Q. and blood lactate response to 1000 kg-m.

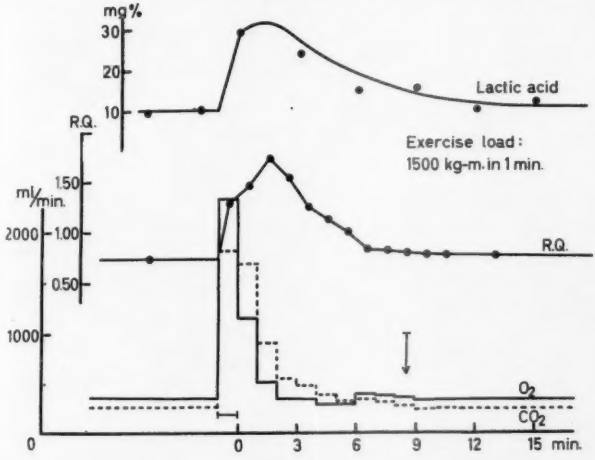

Fig. 18 b.
O_2-intake, CO_2-output (ATPS), R.Q. and blood lactate response to 1500 kg-m.

The respiratory recovery took place at a faster rate in the athlete compared to the nonathlete. In fig. 19 and table 10 are shown data

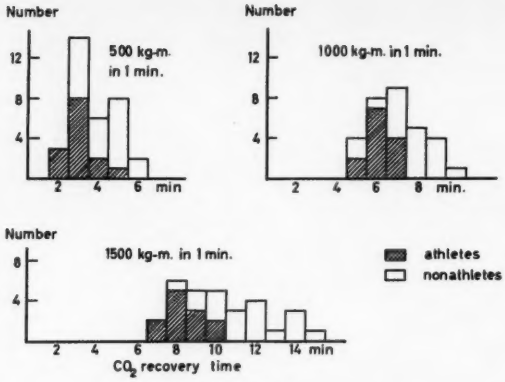

Fig. 19.

Distribution diagrams of CO_2-recovery times following performances of exercise of brief duration. Men, age below 30 years.

for CO_2-recovery time from all the athletes and nonathletes investigated. As seen, the average CO_2-recovery times are less for the athletes than for the nonathletes. A considerable overlapping exists, which is reduced when the workload is increased.

Table 10

CO_2-recovery time (in minutes) of athletes and nonathletes 30 years of age and below

Subjects	Statistical data	Work performed in 1 minute		
		500 kg-m.	1000 kg-m.	1500 kg-m.
Athletes *	No.	14	13	12
	Mean	3.07	6.15	8.42
	St.dev.	0.87	0.73	1.00
	Range	2—5	5—7	7—10
Nonathletes	No.	20	18	18
	Mean	4.35	7.61	11.50
	St.dev.	1.08	1.39	1.69
	Range	3—6	5—10	8—15

* 1 athlete was 31 years of age.

The difference between means of the 1500 kg-m. experiments was found to be statistically highly significant, and that of the 500 kg-m. and 1000 kg-m. experiments significant.

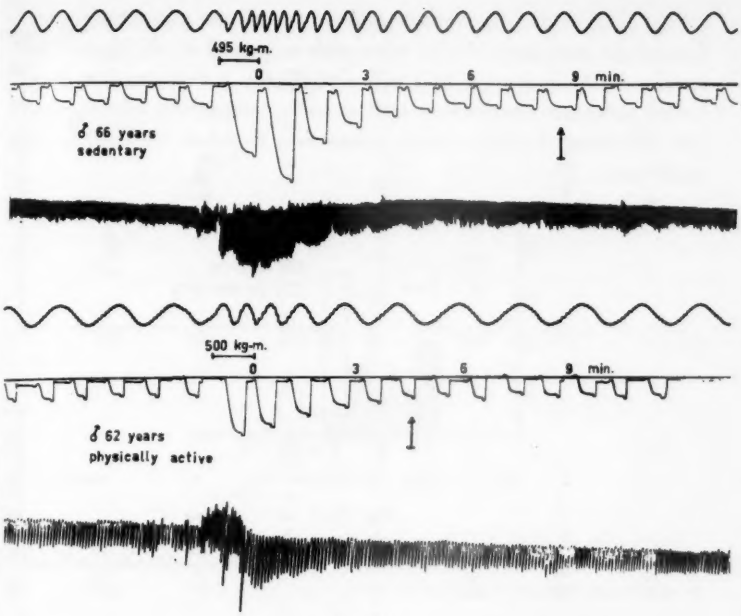

Fig. 20.

Sections of spirometer curves taken from experiments performed on two elderly men with different degrees of physical activity. CO_2-recovery times are marked with arrows.

In fig. 20 are shown sections of spirometer curves taken from a 65-year-old physically active man and a sedentary living man of about the same age and body size. A slower respiratory recovery was observed in the sedentary man, and additionally an elevation of the R.D. line in the post-exercise period occurred.

Table 11

CO_2-recovery time (in minutes)

in sedentary and physically active men between 55 and 70 years of age

Subjects	500 kg-m. in 1 min.				1000 kg-m. in 1 min.		
	No.	Mean	St.dev.	Range	No.	Mean	Range
Physically active	12	5.67	1.36	4— 8	3	8.67	8—10
Sedentary	12	8.17	1.18	6—10	6	12.33	10—15

Fig. 21 gives the distribution diagram for all the experiments performed on men aged 55—70 years with workload of 500 kg-m. The average CO_2-recovery time for the physically active was less than for the sedentary men; however, there was a considerable overlapping. The difference between mean values was found to be statistically significant.

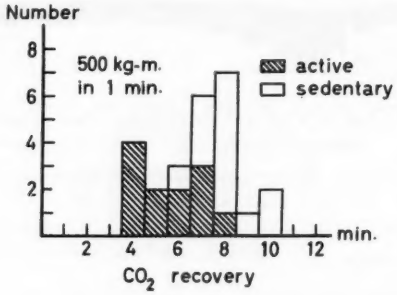

Fig. 21.

Distribution diagram of CO_2-recovery times after performance of 500 kg-m in one min. by men between 55 and 70 years of age. One 70-year-old man is included in this figure, but not in table 11.

Recovery time for oxygen intake and carbon dioxide output in relation to exercise load

The time required for the respiratory gas exchange to reach resting level after bicycling one minute is increased when a higher workload is used, as demonstrated on the spirometer curves presented. In fig. 22 the recovery time for O_2-intake, CO_2-output, pulmonary ventilation and respiratory rate is related to the exercise load, the working time being one minute. Only data from experiments performed on nonathletes below 30 years of age have been plotted. It is seen that the recovery time is increased about in proportion to the workload used. This problem has been further investigated, and the results have been presented in an earlier report (K. L. Andersen and H. Andersen, 1957).

CO_2-recovery time related to body size

By the testing procedure applied in this study the body weight does not influence the amount of work performed on the bicycle. Conse-

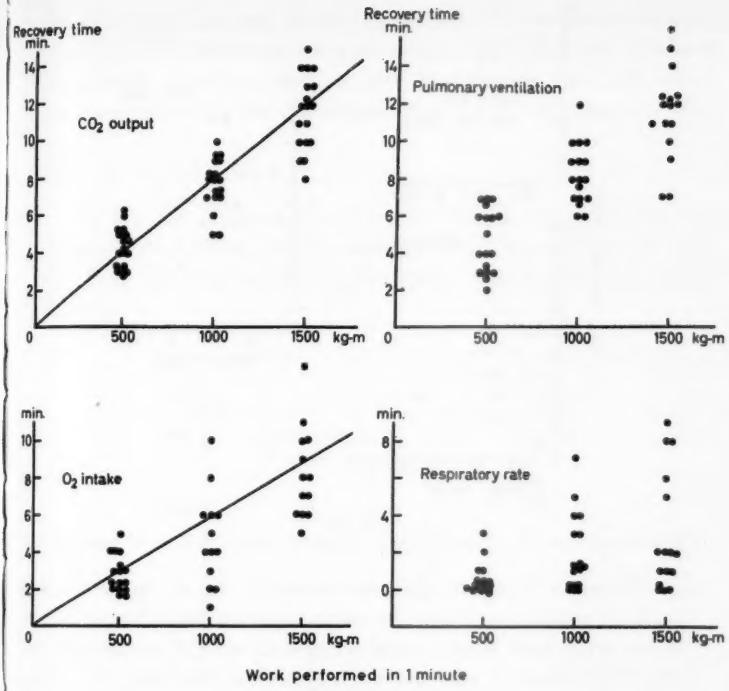

Fig. 22.

Recovery time in relation to exercise load. The diagonal lines are an approximate fit. The figure shows data from 18 nonathletes on whom all the three loads were performed.

quently, absolute quantitative data concerning functional status are obtained. It might therefore be of interest to investigate if and to what extent a relationship exists between respiratory recovery time and the body weight.

In order to exclude the effect of aging only experimental results obtained on subjects below 40 years of age have been used for this purpose. Below this level of age no very obese subjects were tested. In fig. 23 the CO_2-recovery time is related to body weight. As seen, a positive correlation exists, but the data are very scattered.

From table 3 it is apparent that the mean value for body weight of the subjects studied is reduced with age. Considering the large age variations in CO_2-recovery time, it is not likely that the small

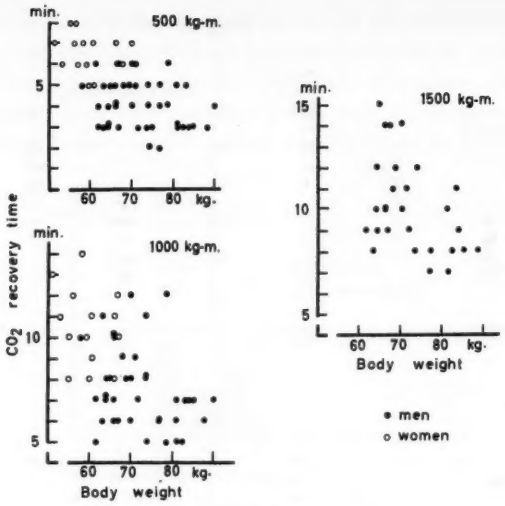

Fig. 23.
CO_2-recovery time in relation to body weight in subjects below 40 years of age.

age differences in weight could be responsible for the age reduction found for respiratory fitness. In order to investigate whether or not differences in body weight could account for sex differences and the differences observed between athletes and nonathletes, the CO_2-

Table 12
CO_2-recovery time (in minutes)
pr. 10 kg body weight in subjects below 30 years of age

Subjects	500 kg-m.			1000 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Athletes *	13	0.41	0.12	13	0.81	0.10
Nonathletes	19	0.64	0.17	16	1.09	0.22
Females	13	1.07	0.22	13	1.81	0.40

Subjects	1500 kg-m.		
	No.	Mean	St.dev.
Athletes *	12	1.09	0.17
Nonathletes	15	1.68	0.35

* 1 athlete was 31 years of age.

recovery time has been divided by weight. The results are shown in table 12. The differences between means are statistically significant. One might therefore conclude that other factors than body weight are responsible for the differences observed in CO_2-recovery time.

Work efficiency

The O_2-cost of the type of exercise used in this study has been determined by adding the O_2-consumption during work and recovery, and from the total subtracting the resting value for the same period of time.

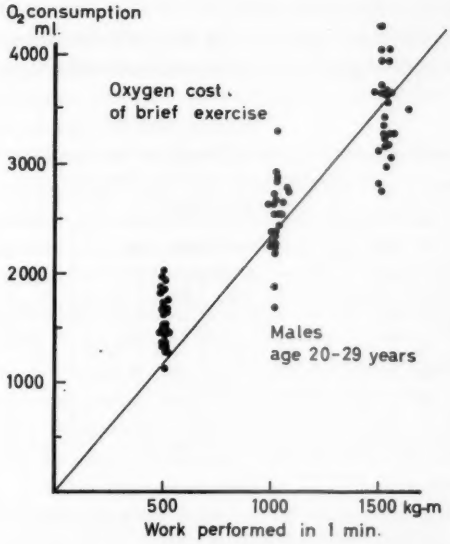

Fig. 24.

Oxygen cost of exercise (STPD) performed in one minute. Diagonal line drawn through zero and mean value for oxygen cost of performing 1500 kg-m.

Data for O_2-cost of exercise are shown in fig. 24. It is evident that performance of 500 kg-m. in one minute requires a relatively larger oxygen consumption than when higher workloads are used. If the oxygen cost of bicycling "no load" had been subtracted from the total work metabolism instead of the resting value, this difference probably would have been reduced.

Considerable spread exists in the data, showing interindividual differences in work efficiency for this type of work.

The net work efficiency has been calculated by assuming that 1 liter of oxygen (at STPD) corresponds to 4.9 Cal., and the figures are given in tables 13 and 14. The mean values for net work efficiency when bicycling in "a steady state" are reported to range from 20 to 25 % (Wahlund, 1948). The lower mean values observed in this study are probably caused by the type of exercise performed. The energy to this short durative exercise is delivered by aerobic as well as anaerobic processes in the working muscle cells, and it has been found that efficiency is less for anaerobic than for aerobic work (Christensen and Högberg, 1950).

The interindividual differences in net work efficiency might well be a causal factor in producing interindividual differences concerning

Table 13
Net work efficiency (in %) in relation to age by performances of exercise loads of brief duration
Men and women

Age in years	500 kg-m.			1000 kg-m.			1500 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.	No.	Mean	St.dev.
20—39	57	16.8	2.42	47	20.4	2.90	26	21.5	2.32
40—69	40	16.4	2.88	15	20.9	2.99	—	—	—
70 and over	29	19.8	4.02	—	—	—	—	—	—

Table 14
Net work efficiency (in %) in relation to sex and physical activity by performances of exercise loads of brief duration
Age below 30 years

Subjects	500 kg-m.			1000 kg-m.			1500 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.	No.	Mean	St.dev.
Athletes **	13	16.0	2.70	13	20.2	3.20	12	22.2	1.94
Nonathletes	17	17.0	2.44	12	19.4	3.18	14	20.6	2.55
Women	13	17.2	1.54	14 *	20.3	2.14	—	—	—

* 1 woman was 33 years of age
** 1 athlete was 31 years of age

metabolic recovery times. Tables 13 and 14 show that the mean values for work efficiency are practically the same in young and old subjects, in men and women, and in athletes and nonathletes. Consequently, the age and sex difference in respiratory recovery time cannot be caused by variability in the net work efficiency only, neither can it explain the differences found between athletes and nonathletes.

Discussion

The O_2- and CO_2-recovery time

The method used in this study does not permit any accurate determination of O_2-intake in as short periods as one minute. Consequently, data concerning O_2-recovery time have not been presented, except for oxygen recovery time measured on "ideal" spirometer curves from young men (fig. 22).

These data revealed that the O_2-debt was paid off at a faster rate than the CO_2-elimination, this observation corroborating results reported by other investigators previously referred to. Although the data for O_2-recovery time in relation to age and sex are not presented, it might be worth while to mention that in general the same differences as found for CO_2-recovery time were observed.

Erikson (1953) determined the CO_2-recovery time following performance of 500 kg-m. in one minute on a small number of healthy young adults, and found that the CO_2-recovery time ranged from 2—5 minutes, these data fitting well with results reported in the present study. Erikson (1957) also investigated Eskimos and white men living at Point Barrow in Alaska, and found that the CO_2-recovery time averaged 9.8 minutes for Eskimos and 11.5 minutes for the white men when performing about 1100 kg-m. in one minute. The young untrained men studied here averaged 7.6 minutes when exercising 1000 kg-m. in one minute, the difference probably being caused by performance of unequal workloads.

The respiratory recovery of healthy subjects in relation to age has been considered by Berg (1947). He determined O_2- and CO_2- half time recovery constants following stepping up on to and down from a bench, and observed increased slowness of CO_2 elimination in elderly compared to young subjects. The CO_2-half time constant of 60-year-old men was nearly double that of 20-year-old men. Although

a direct comparison between Berg's data and the data reported here cannot be made, the age trends in this study were found to be practically the same. The average CO_2-recovery time for men between 20—30 years was 3.8 minutes compared to 7.4 minutes for men between 50 and 59 years.

In this study subjects up to 96 years of age were tested, and furnish further evidence to show the deterioriation of respiratory and circulatory fitness which occurs as an effect of aging. The CO_2-recovery time observed in the subjects above 80 years ranged from 9—14 minutes after 500 kg-m. in one minute. This exercise load is light for young subjects, most of these probably being able to perform this load indefinitely without discomfort. It was frequently observed that when this load led to a recovery time of more than 10 minutes, the subjects suffered from dyspnoea and general discomfort during work and the first part of recovery. It is believed that in such cases the cardiorespiratory function is so reduced that the subjects are bound to a life not requiring a metabolic rate very much above the resting level.

Statistically significant sex differences were found in the youngest age groups. As demonstrated, differences in body size or net work efficiency cannot account for this difference. The experimental results correspond well with the daily life experience concerning women's fitness for hard muscular work, which, in general, is less than for men of corresponding age. It might be that the females' lower fitness for work is due to less physical training; this topic will be dealt with later, in the general discussion, p. 92.

There exists overlapping between men and women in the youngest age group concerning CO_2-recovery time. This overlapping is more pronouced in the oldest age group, and, as seen from the figures and tables presented, it is doubtful if any sex difference exists at all for subjects above 70 years of age.

The effect of physical training on the rate of decrease of O_2-intake and CO_2-output during recovery from exercise was studied by Simonsen (1926) and Berg (1947). They both found a more rapid decrease at the end of a physical training regimen.

Although other factors than physical training may be responsible for physiological differences observed between athletes and non-athletes, it is most likely that quicker respiratory recovery observed in athletes is caused by the training regimen they have undertaken.

The quicker respiratory recovery found in physically active compared to sedentary elderly men also indicates a beneficial effect of training on the respiratory and circulatory functions of subjects in the advanced age.

Physiological factors influencing the respiratory recovery time

As stressed in the introduction it is well established that an O_2-deficit is built up in the body at the very beginning of exercise. This deficit remains as a debt during the whole exercise period, at which end there also exists a surplus of carbon dioxide. During the recovery period the O_2 debt is paid off and the surplus of CO_2 removed from the body. If lactic acid is produced in the muscle cells and poured into the circulating blood, this influences the CO_2-output during work and recovery.

The rate at which the restoration of the normal resting "steady state" value for respiratory gases takes place depends on the following physiological mechanisms:

1. The gas exchange between the cells and the blood circulating through the tissue.
2. The local blood flow through the tissue.
3. The heart minute volume.
4. The function of the lungs involving the gas exchange between the blood and the atmospheric air.
5. The transporting capacity of the blood for the respiratory gases.
6. The nervous and chemical regulation of circulation and respiration.
7. The amount of lactic acid produced in the working muscles.

In order to evaluate the importance of each of these factors in producing the interindividual differences observed in respiratory recovery time further experimental work is necessary. In this study investigation of ventilatory capacity of the lungs, heart rate and blood lactic response to exercise was undertaken, and these results will be briefly discussed.

The rate of blood flow through the body as a whole depends upon the amount of blood the heart pumps per minute. It is evident that a low heart minute volume may slow down the circulation time from the tissue to the lungs, or vice versa, thus also influencing the rate

at which the metabolic recovery from muscular exercise takes place. Further, the amount of blood irrigating the working muscles is influenced by the heart minute volume.

The determinations of heart rate response to the exercise loads undertaken in this study revealed definite differences between young and old subjects. The heart rate adapted to and recovered from the exercise stress at a much slower rate in the old compared to the young subjects. The maximal increase observed during the exercise was very much lower in the old compared to the young subjects. These data indicate similar trends concerning cardiac output.

The importance of the central circulatory system for the metabolic revovery time following an exercise load has been instructively demonstrated by Erikson (1953) in his study of a patient suffering from a valvular heart disease. Prior to a valvotomy the CO_2-recovery time after performance of 500 kg-m. in one minute was found to be 12 minutes, which was reduced to 6 minutes by the operation.

As it was obvious that some of the old subjects used exceptionally high volumes of pulmonary ventilation to blow off the carbon dioxide produced during and after the exercise period, the question was raised whether or not the ventilatory capacity of their lungs was a limiting factor. Consequently, the bellows function of the lungs was determined by measuring the vital capacity and the voluntary maximal breathing capacity. The data revealed statistically significant age deterioration in this part of the lung function. However, considering that the maximal breathing capacity averages 65 l. for men and 47 l. for women above 70 years of age, and that similar data for vital capacity are 2708 ml. and 2064 ml., it is apparent that for old people also large reserves exist for this part of the lungs function. It is believed that it is most unlikely that the bellows function of the lungs is a limiting factor for the fitness for work of the average old person.

However, in some few elderly subjects very low values for the lung volumes and breathing capacity were found. For instance, the maximal breathing capacity of a 71-year-old woman was 18 liters and the vital capacity 1100 ml. In such a person it might be that the ventilatory capacity of the lungs becomes a limiting factor for the physical working capacity.

The lactic acid studies are discussed in detail in the chapter on blood lactate, page 65.

The respiratory quotient

During the one-minute exercise period a fairly constant R. Q. drop below the resting level was observed. As the determination of O_2-intake in as short intervals as one minute is inaccurate when the spirometer technique is used, the R. Q. drop was verified in a few experiments by collecting the expired air in a tank and analyzing this for CO_2- and O_2-content by means of Scholander's ½ cc. gas analyzer.

A hyperventilation relative to the amount of blood irrigating the lungs at the very beginning of muscular exercise might well be considered to be responsible for the R. Q. drop. This would in any case reveal itself by a reduced CO_2-tension (pCO_2) of arterial blood and alveolar air. No determinations of pCO_2 have been carried out. It might be that the pCO_2-reduction is too small to be measurable, but still sufficient to produce the R. Q. drop. Further studies directed on this problem are in progress.

Another mechanism to consider is differences in transportation time for CO_2 from the tissue to the lungs and for O_2 from the lungs to the tissue. As is known, the metabolic CO_2 is transported in the veins from the tissue to the right side of the heart, and further through the lung arteries to the lung. This CO_2-transportation time is slow compared with the time used for transportation of O_2 from the lungs to the tissue, which takes place through the arterial system. except for the short distance from the lungs to the left side of the heart. This difference might be expected to result in a lag concerning output of metabolic produced CO_2 compared to O_2-intake.

After cessation of work the R. Q. rises, in some experiments above unity, showing that an excess CO_2-output beyond that metabolically produced takes place. When young males performed 500 kg-m. in one minute this postexercise R. Q. elevation was small, and exceeded unity in only a few experiments. In elderly subjects an elevation of the R. D. line above the preexercise level was seen as a fairly constant phenomenon, giving an R. Q. of above unity for a shorter period of time in the recovery period.

Performance of 1000 kg-m. in one minute led to a considerable elevation of the R. D. line in women, elderly men and physically untrained young men. By performance of 1500 kg-m. the difference in postexercise R. D. elevation is great when athletes are compared

with nonathletes, the latter having the most striking elevation, giving R. Q. values far above unity for a shorter period of time.

This elevation of the R. D. line and the rise of R. Q. above unity indicates occurrence of increased lactic acid content of the circulating blood in the postexercise period, which also has been verified by the blood studies undertaken. By comparing the shape of the R. D. line with the shape of the curve for lactic acid content of the blood during recovery a similarity is seen in the figures demonstrated. Similar results were obtained by Scholander, who used the same spirometer technique in diving experiments on seals and birds (1940). Scholander concluded that the shape and the degree of R. D. elevation in the period following a dive could be used as a rough indirect measurement of the lactic acid increase of the blood. The results found in this study supply further evidence in support of this statement.

The R. Q. of the total work metabolism has been calculated, presuming that the metabolic rate of the body outside the working muscle tissue remains at the resting level. Values above unity were frequently observed, which of course cannot reflect the real metabolism, as this never results in an R. Q. above 1.00. Similar observations have been carried out by several authors, such as Hill et al. (1923-4) in their extensive studies of metabolic recovery from strenuous exercise. In the interpretation of this phenomenon they suggested that the presumption of an unchanged metabolism in the body outside the working muscle tissue was wrong, and that this fault was responsible for the miserable R. Q. values calculated. This may well be the cause. However, as far as is known by the author, no experimental evidence in man is available that points to any safe conclusion on this problem.

However, it might well be that the excess CO_2-output beyond the metabolic produced CO_2 which has been shown to take place in the first part of recovery, is not retained within a reasonable period of time. If thus the CO_2-stores in the body are reduced for a longer period than used for studying the recovery period, it would of course result in a high R. Q. This has also been shown to be true, the problem having been further investigated and the results published elsewhere (Bugge-Asperheim and Andersen 1957).

Summary and conclusions

The gas exchange was continuously recorded before, during and after standard exercise loads in healthy adult subjects; 105 males and 35 females, ranging in age from 16 to 96 years, were tested. Three different workloads were used: 500, 1000 and 1500 kg-m., bicycled in one minute. In this chapter the O_2-intake and CO_2-output were considered. The results show briefly:

1. The oxygen debt was paid off before the CO_2-output reached the resting level.
2. Age differences for CO_2recovery time were found. The lowest recovery time was observed in the ages between 20 and 30. From the age of 30 the recovery time increases and in men is about doubled at the age of 70.
3. Women were found to have a longer CO_2-recovery time than men. The magnitude of this difference was reduced in the advanced age groups, and above 70 years of age it is doubtful if any sex differences exist at all.
4. Athletes have a shorter respiratory recovery time than non-athletes. A considerable overlapping exists between the two groups, which is reduced when workload is increased. Physically active elderly men have on average a shorter respiratory recovery time than sedentary elderly men.
5. For work performed in one minute the respiratory recovery time is about linearly proportional to the workload in men below 30 years of age.
6. A slightly positive correlation was found between body weight and CO_2-recovery time for subjects below 40 years of age. Differences in body weight could not account for the observed sex differences or for the differences between athletes and non-athletes.

PULMONARY VENTILATION

When muscular exercise is performed in a "steady state" of respiratory gas exchange, there exists an almost linear relationship between oxygen intake and pulmonary ventilation (Christensen 1932). At great work intensities it shows a relatively larger increase and does not bear a constant relation to the oxygen consumption; the reason for this is but incompletely understood (Robinson 1938, Asmussen and Nielsen 1946, Aastrand 1952, Georg 1952).

The ventilatory equivalent for oxygen intake during work, i. e. the rate of ventilation per unit of oxygen intake shows interindividual differences, which to some extent are also present at rest (Anthony 1930, 1937). It is reported that children on average have a larger ventilatory equivalent for oxygen than adults and that females average higher than males (Aastrand 1952). Old healthy men are reported to have a higher ventilatory equivalent for oxygen than young men; however, considerable overlapping exists (Norris et al. 1955, Durnin and Miculicic 1956). Compared with healthy subjects exceptionally high values for pulmonary ventilation have been observed in cardiac patients during performances of "steady state" exercise (Eskildsen 1945).

Concerning types of work in which a "steady state" is not obtained, it is necessary to consider the pulmonary ventilation, O_2-intake and CO_2-output not only during work, but in addition during the whole recovery period, in order to work out interrelations.

The extra ventilation caused by a brief standard workload, that is, the amount of pulmonary ventilation above the resting level during exercise and recovery, has been considered by Erikson (1957). The amount of extra ventilation was found to be better correlated to the extra CO_2-output than to the O_2-cost of exercise. Further, exceptionally high values for extra ventilation were observed in patients suffering from cardiac diseases. This finding was confirmed by Fodstad (1956).

Here will be presented the calculated figures for the extra ventilation of healthy adults performing the exercise loads used in this study. These data have been related to age and sex, and the influence of physical activity has been investigated. The relationship between extra ventilation, O_2-cost of exercise and extra CO_2-output has been established within the limits of the data obtained. In addition the recovery time for pulmonary ventilation and respiratory rate has been considered.

Results

Extra ventilation in relation to workload

The extra ventilation caused by the exercise load was calculated by adding the pulmonary ventilation during exercise and recovery, and from the total subtracting the resting value for the same period of time, this being the average of the pre- and post-exercise level.

In fig. 25 the absolute values for extra ventilation against age are

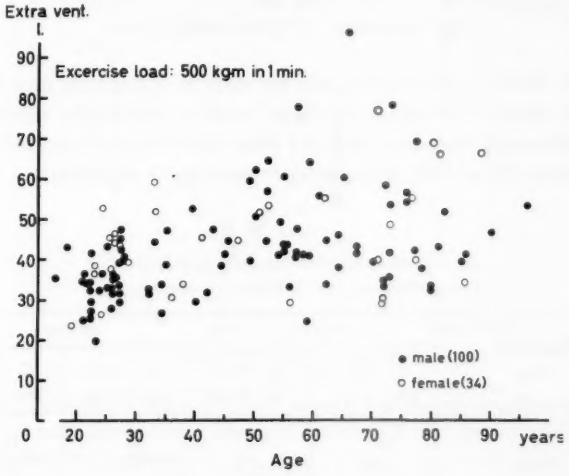

Fig. 25.
Extra ventilation (BTPS) in relation to age.

plotted, the workload being 500 kg-m. in one minute. The same relationship during bicycling at 1000 kg-m. in one minute is shown in fig. 26. Age differences are clearly reflected in the diagrams; however, considerable overlapping exists.

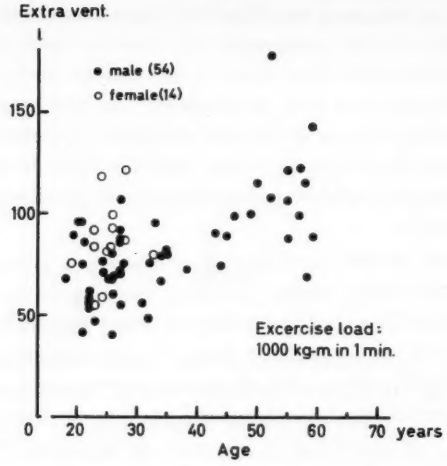

Fig. 26.
Extra ventilation (BTPS) in relation to age.

The difference between means for extra ventilation in men below 30 and above 70 years at 500 kg-m. work is statistically significant. The difference between means for extra ventilation in men below 30 and above 50 at 1000 kg-m. work is statistically significant.

Table 15

Extra ventilation (in liters at BTPS)
by performance of 500 kg-m. in one minute

Statistical data	Men		Women	
	* 30 years and below	70 years and above	30 years and below	70 years and above
No.	21	20	13	11
Mean	35.8	47.2	38.2	50.2
St.dev.	6.8	12.3	8.6	17.4
Range	20—47	34—78	24—52	27—77

* Nonathletes

Table 16
Extra ventilation (in liters at BTPS)
by performance of 1000 kg-m. in one minute

Statistical data	Men		Women
	* 30 years and below	50 years and above	30 years and below
No.	18	12	13
Mean	77.4	113.2	86.6
St.dev.	16.6	28.1	20.0
Range	48—108	69—179	56—121

* Nonathletes

Sex differences exist for extra ventilation with a larger extra ventilation in women than men. However, these differences are statistically insignificant.

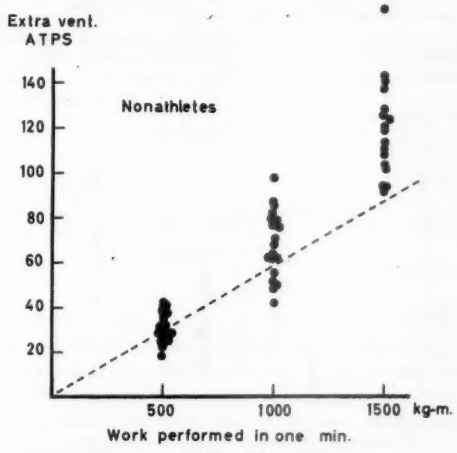

Fig. 27.

Extra ventilation in relation to work performed in one minute. Diagonal line is drawn through zero and mean value of the extra ventilation caused by performance of 500 kg-m in one minute.

In fig. 27 is plotted extra ventilation in young nonathletes when performing 500, 1000 and 1500 kg-m. in one minute, and the same relationship for athletes is shown in fig. 28. It is apparent that extra ventilation of athletes increases about in proportion to the workload performed. For nonathletes this linear proportionality does not exist, as the higher workloads give larger extra ventilation.

Table 17
Extra ventilation (in liters at BTPS)
in athletes and nonathletes

Subjects	500 kg-m.			1000 kg-m.			1500 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.	No.	Mean	St.dev.
Athletes	13	33.7	6.4	11	62.5	14.4	11	97.0	20.1
Nonathl.	21	35.8	6.8	18	77.4	16.6	17	132.9	20.3

Table 18
Extra ventilation (in liters at BTPS)
in elderly physically active and sedentary men

Subjects	500 kg-m.			1000 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Active	10	42.3	10.9	3	101.3	—
Sedentary	12	53.6	18.0	6	108.6	—

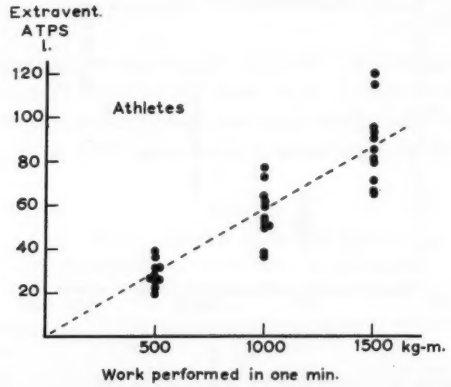

Fig. 28.

Extra ventilation in relation to work performed in one minute. Diagonal line is drawn through zero and mean value of the extra ventilation caused by performance of 500 kg-m in one minute.

Table 17 gives average values for extra ventilation in athletes and nonathletes, and table 18 for elderly physically active and sedentary men. The physically active men average lower in extra ventilation when performing the same amount of work. The differences between

means are statistically significant for the 1500 kg-m. work, though elsewhere insignificant.

Extra ventilation related to O_2-cost of exercise and extra CO_2-output

O_2-cost of exercise has been calculated by the procedure described previously. The extra CO_2-output during work and recovery is calculated in a similar way.

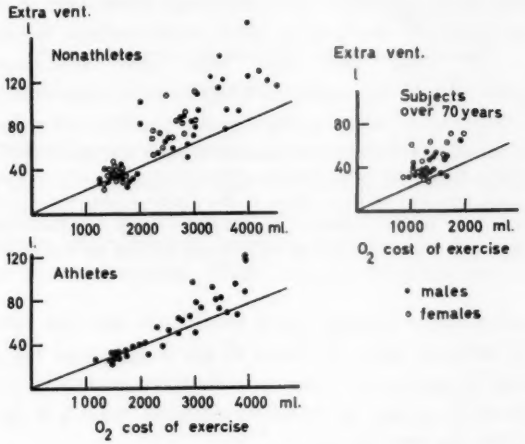

Fig. 29.

Relationship between oxygen cost of exercise and extra ventilation. Diagonal lines for athletes and nonathletes are drawn through zero and cross section points between mean values of oxygen cost and extra ventilation of performing 500 kg-m in one minute. The diagonal line on the figure representing subjects over 70 years of age has the same slope as that for nonathletes. All volumes are given at ATPS.

Fig. 29 shows the relationship between O_2-cost of exercise and the extra ventilation.

By drawing a line through zero and the cross section point between the average of O_2-cost and extra ventilation of performing 500 kg-m. (which for men below 30 years of age is practically "alactic") it is apparent that the relationship is closer to linearity for athletes than for nonathletes.

For the same metabolic rates the extra ventilation of elderly subjects is higher than for the younger, as seen from fig. 29.

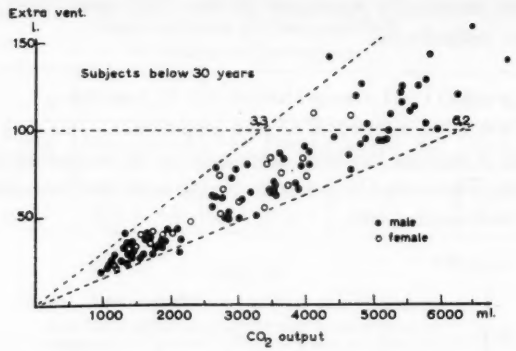

Fig. 30.

Total CO_2-output in relation to extra ventilation. The broken diagonal lines are points between the broken horizontal line drawn from 100 l. extraventilation and drawn through zero and extreme values of the observed data. Cross intersections points between the broken horizontal line drawn from 100 l. extraventilation and diagonal lines give average percentage CO_2 in the expired air. Volumes are given at ATPS.

The relationship between extra ventilation and the extra CO_2-output of subjects below 30 years of age is shown in fig. 30. This relationship is apparently closer than that between extra ventilation and O_2-cost of exercise, as would be expected, as CO_2 is the normal stimulus for the ventilation.

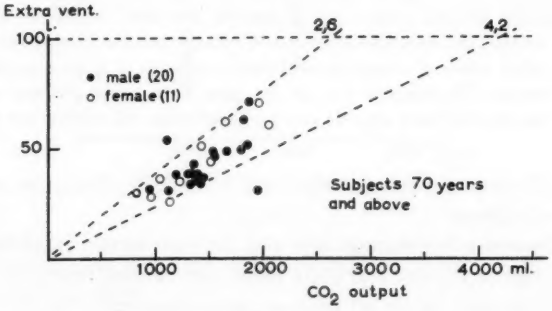

Fig. 31.

Total CO_2-output in relation to extra ventilation. Broken cross lines mark limits for extreme values with exceptions of two figures, one above and one under. Cross point with broken horizontal line drawn from 100 l. extra ventilation gives average percentage CO_2 in the expired air. Volumes are given at ATPS.

In fig. 31 is shown the relationship between extra ventilation and extra CO_2-output of subjects over 70 years of age. By drawing the horizontal line from the ordinate point corresponding to 100 l. of extra ventilation, the percentage of CO_2 in the volume of expired air can be determined by extra polation, as shown in the figure. It is seen that this percentage ranges from 2.6 to 4.3 (except for two subjects, one lower and one higher), the figures for young adults being 4.2 to 5.8 (fig. 31). This difference between young and old subjects is apparently significant in a statistical term, although no arithmetical analyses have been carried out in order to test the significance.

This difference in ventilation efficiency can also be demonstrated by dividing the extra ventilation by the extra CO_2-output (volumes at ATPS). This quotient is named ventilatory equivalent for CO_2-output and is expressed as liter ventilation per liter exhaled CO_2.

No statistically significant difference in ventilatory equivalent for CO_2-output was observed between athletes and nonathletes nor between men and women. These data are not presented.

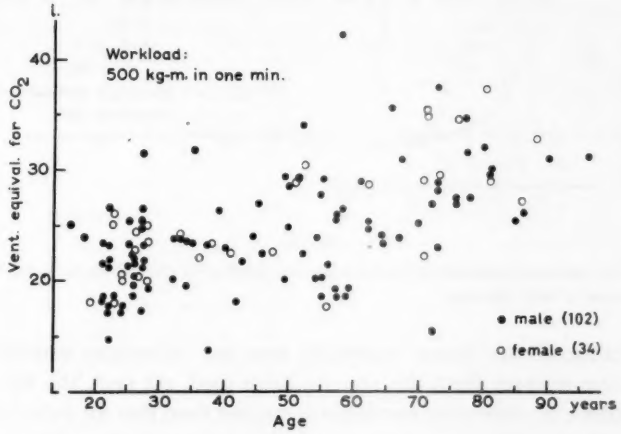

Fig. 32.

Ventilatory equivalent for CO_2-output (i.e. amount of extra ventilation per liter of total CO_2-output) in relation to age. The equivalent is calculated from volumes at ATPS.

Fig. 32 gives the ventilatory equivalent for CO_2-output in relation to age. This is almost unchanged up to the age of about 70 years, but

is definitely increased in the oldest subjects. The differences between means of subjects below 30 and above 70 years of age are statistically significant.

Relation between recovery time for pulmonary ventilation, respiratory rate and CO_2-output

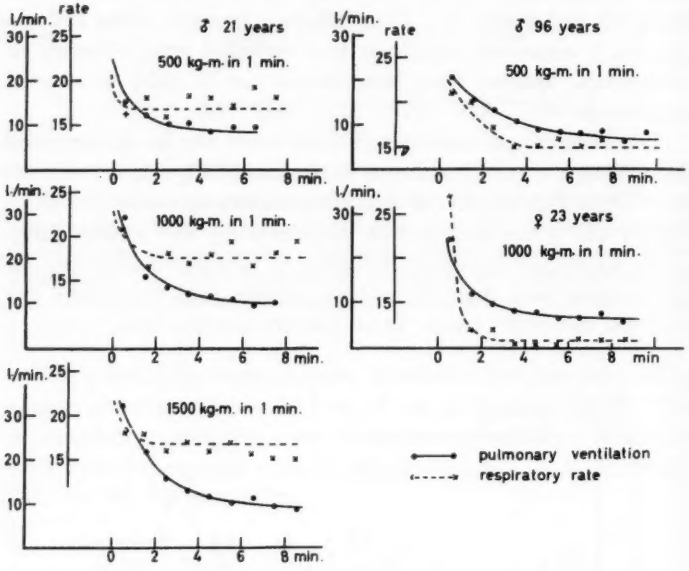

Fig. 33.

The decrease of pulmonary ventilation and respiratory rate during recovery from exercise of brief duration.

In fig. 33 are shown respiratory rate and pulmonary ventilation during recovery from the exercise loads used. As seen, the rate of decrease of respiratory frequency is quicker than that for pulmonary ventilation. This means that the increased ventilation during the later part of recovery is due to enlarged Tidal volume.

In fig. 34 is shown the relationship between recovery time for pulmonary ventilation and respiratory rate. The correlation must be judged to be but poor. Evidently, the recovery time for pulmonary ventilation cannot be predicted by considering the rate only.

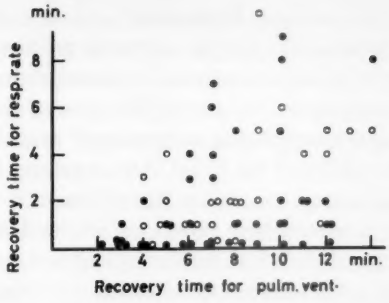

Fig. 34.

Relation between recovery time for pulmonary ventilation and respiratory rate. Data from women (13) and nonathletes (20) performing 500, 1000 and 1500 kg-m in one minute are plotted.

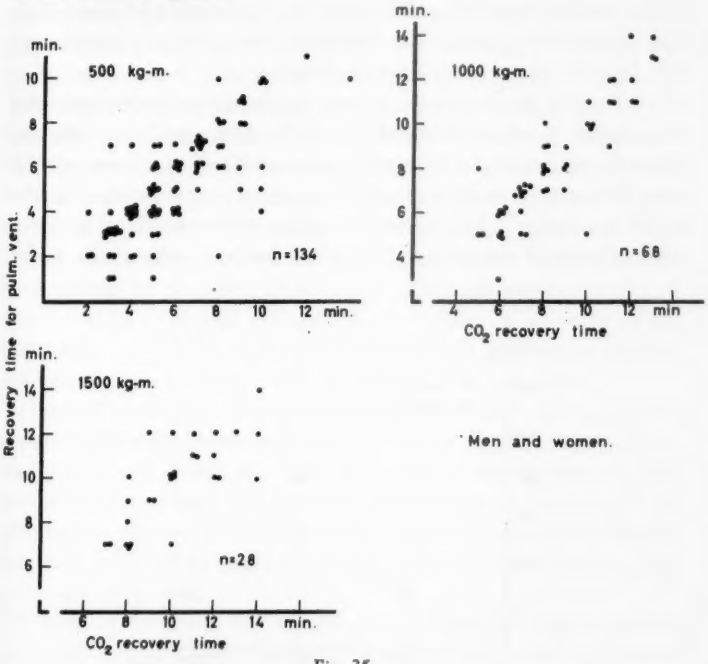

Fig. 35.

Relationship between recovery time for pulmonary ventilation and CO_2-output.

In fig. 35 is shown the relationship between recovery time for pulmonary ventilation and CO_2-output.

Discussion

The causal mechanisms for the increased pulmonary ventilation during exercise have been considered by several authors, but are still incompletely understood. Nielsen (1936) showed that the increase in pulmonary ventilation during exercise is not caused by an increase in pCO_2, or in acidity of the blood. Asmussen and Nielsen (1946) studied the pulmonary ventilation during heavy exercise and concluded that the relatively large ventilation observed during strenuous exercise was caused by some substance which is produced in the working muscle cells, and which influences the respiration through the arterial chemoreceptors. This substance, although closely related, was not lactic acid. The hypothesis was advanced that it was a product from the anaerobic processes in the working muscle tissue.

The results observed in this study are in accord with these findings, as high blood lactate was frequently seen without a corresponding elevation of the pulmonary ventilation.

It is suggested that the work load which brings about outpouring of anaerobic products in the blood can be determined from the diagram showing the relationship between workload and extra ventilation. When no anaerobic metabolites appear in the blood, this relationship is linear. The linearity is broken at the workload at which accumulation of anaerobics in the blood becomes measurable. In fig.

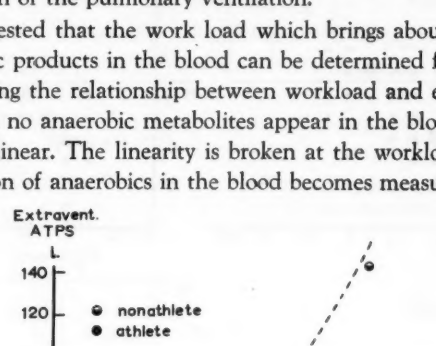

Fig. 36.

Extra ventilation in relation to work performed in one minute. The figure demonstrates difference between an athlete and a nonathlete.

36 are plotted data obtained from experiments on a champion athlete and a sedentary young man. The breaking point on the curve taken from the latter corresponds to a workload of about 900 kg-m. There is a linear proportionality up to 1500 kg-m. on the curve representing the champion athlete. Experiments using higher workloads have not been conducted on him.

It is believed that determination of this breaking point might be used as a physical fitness test, giving information about how large a workload can be performed without resulting in considerable anaerobic energy delivering processes in the working muscles.

A statistically significant higher ventilatory equivalent for CO_2-output or a lower percentage of CO_2 in the expired air was observed in the very old compared to the young subjects. Although no experimental investigations were undertaken to settle the problem of which physiological factors are responsible for this difference, this topic will be discussed briefly in terms of the present available knowledge.

A slightly higher pulmonary ventilation has been found in old compared to young subjects (Georg 1952, Norris et al. 1956), the alveolar ventilation being practically the same because reduced Tidal volume and increased respiratory rate balanced each other. It might therefore be that the difference in ventilatory equivalent for CO_2-output would have been reduced if extra alveolar ventilation had been related to the extra CO_2-output. Although no calculation of alveolar ventilation was undertaken, the difference observed in the percentage of CO_2 in expired air between old and young subjects is believed to be too large to be ruled out by this procedure.

It is well established that the fresh air which enters the respiratory organs is unevenly distributed within the lungs (Comroe et al. 1955), and it has been found that the magnitude of this uneven ventilation is larger in elderly than in young subjects, due to development of emphysema (Georg 1955). The higher degree of uneven ventilation would be expected to result in a higher pulmonary ventilation at the same metabolic rate.

If parts of the lungs are not circulated with blood, but are ventilated with air, the result would be a higher ventilatory equivalent for CO_2-output.

The diffusibility for gas through the alveolar membranes and the efficiency of the nervous and chemical regulation of respiration and circulation should also be borne in mind.

Summary and conclusions

Large interindividual differences in extra ventilation were found in subjects when performing the same amount of work. In order to elucidate this problem the extra ventilation was related to age and sex and the influence of physical activity was considered. Further, the relationship between extra ventilation, O_2-cost of exercise and extra CO_2-output has been established within the limits of the experimental data on hand. In addition the recovery time for pulmonary ventilation and respiratory rate has been considered.

The results show briefly:

1. When performing the same amount of work, the extra ventilation increases with age. Women have on average larger extra ventilation than men. Physically active men have on average a lower extra ventilation than sedentary men. The differences of mean values are statistically significant between subjects below 30 years and above 70 years at the 500 kg-m. exercise, between subjects below 30 years and above 50 years at the 1000 kg-m., and between athletes and nonathletes at the 1500 kg-m. load. The differences between means of the other group are statistically insignificant.
2. Extra ventilation of athletes increases about in proportion to the work performed, and to the O_2-cost of exercise with some few exceptions. In nonathletes this linear relationship does not exist, as the higher workloads give a larger extra ventilation.
3. It was shown that the extra ventilation was larger whenever the exercise led to increased blood lactate.
4. The average percentage of CO_2 in the amount of extra ventilation was lower in the oldest than in the youngest subjects. The cause of this difference was discussed in terms of the present available knowledge on the subject.
5. The respiratory rate returns faster to resting level than the pulmonary ventilation.
6. The recovery time for pulmonary ventilation cannot be predicted by considering the rate only.

BLOOD LACTATE

During the recovery period following completion of the brief standard exercise loads used for the respiratory studies, an elevation of the R. D. line above the preexercise level took place in many of the experiments, which indicates increased lactic acid in the circulating blood.

In order to study this problem further, the blood lactate pre- and postexercise was determined at regular intervals in a limited number of subjects. In addition the pH and the total CO_2-content of arterial blood were investigated in a few experiments in order to demonstrate the influence of increased lactic acid content on the anion-cation balance.

Results

Blood lactate

Fig. 37 gives the average pre- and postexercise values for blood

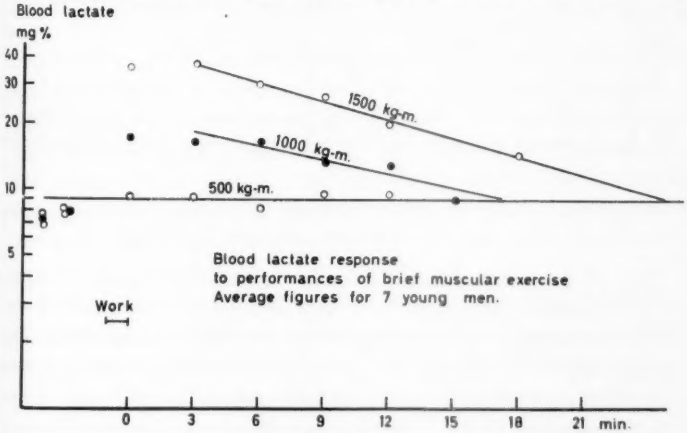

Fig. 37.

Blood lactate response to exercise loads performed by young men. Mean values of 7 subjects. Data plotted on semilogarithmic graph paper.

lactate of capillary blood taken from young males at workloads of 500, 1000 and 1500 kg-m. in one minute.

Performance of 500 kg-m. did not increase the blood lactate, while the two highest workloads resulted in a striking elevation. The peak blood lactate was reached 2—5 minutes after completion of work. From then on the lactate concentration fell slowly down to resting level, following a curve, the shape of this being almost exponential.

A close relation between the shape of the R. D. line and the shape of the blood lactate curve was found. This relationship is demonstrated in fig. 40. The topic has been discussed previously, page 50.

Further, it was observed that the blood lactate remained elevated for a longer period of time than the O_2-intake and CO_2-output.

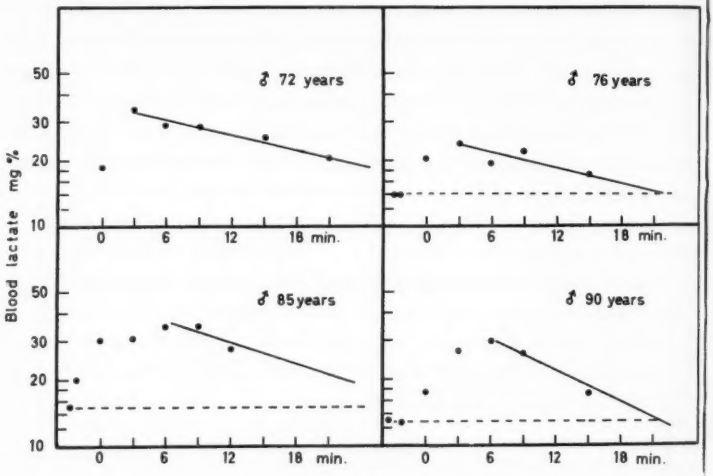

Fig. 38.

Blood lactate response to performance of 500 kg-m in one minute of 4 subjects over 70 years of age. Data plotted on semilogarithmic graph paper.

Fig. 38 shows blood lactate response to performance of 500 kg-m. in one minute undertaken by 4 male subjects over 70 years of age. In all the subjects studied a significant elevation was observed. The peak values were reached 5—7 minutes after cessation of work, this time being considerably longer than observed for young males when they performed work which led to an elevation of the blood lactate.

In fig. 39 are shown data for blood lactate response to performances of 500 and 1000 kg-m. in one minute undertaken by young females.

The 500 as well as the 1000 kg-m. load led to a significant elevation in the recovery period, the latter giving the higher maximal values. The peak values were reached 2—5 minutes after completion of exercise.

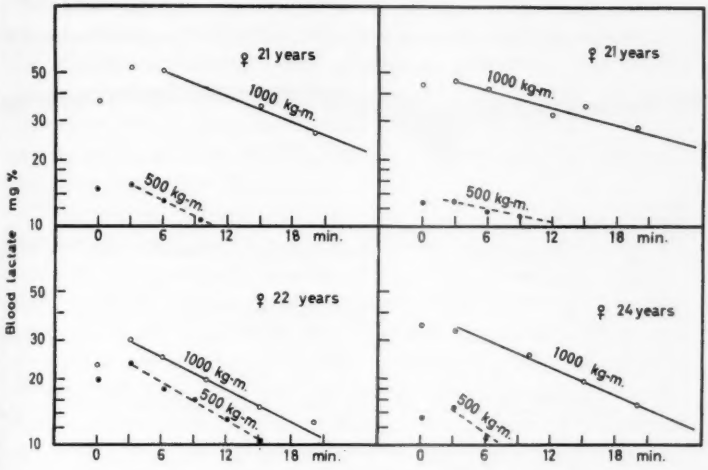

Fig. 39.

Blood lactate response to performance of brief exercise of 4 young females. Data plotted on semilogarithmic graph paper.

Difference in blood lactate response observed between an athlete and a nonathlete is demonstrated in figs. 17 and 18. Performance of 1000 kg-m. in one minute did not increase the blood lactate in the athlete, while the increase was considerable in the nonathlete. Performance of 1500 kg-m. in one minute resulted in elevated blood lactate during recovery in the athlete as well as in the nonathlete, the latter showing the larger increase.

Total CO_2-content and pH of arterial blood

Total CO_2-content and pH of arterial blood were measured in three young males, one performing 500, the other 1000 and the third 1500 kg-m. in one minute, none of them being athletes. The brachial artery was punctured with a Wassermann needle, which remained in the artery during the whole experiment. Blood was drawn anaerobically at regular intervals and total CO_2-content was measured

with van Slyke's gas-analytical apparatus. pH of the blood was measured anaerobically (under oil) with a Beckman pH meter, the blood being at 37° C.

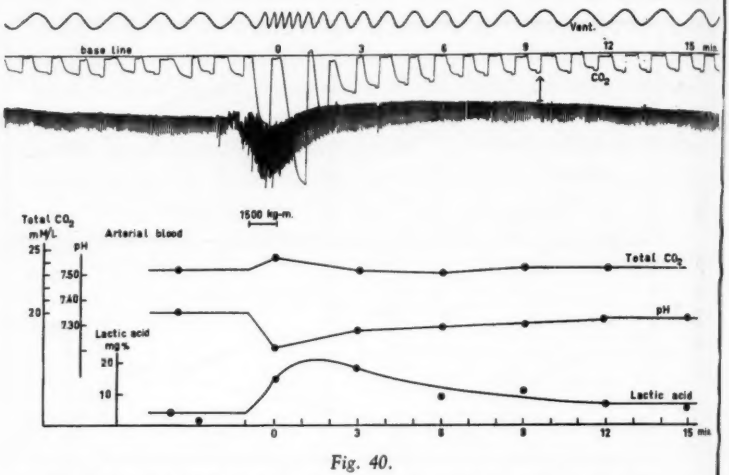

Fig. 40.

Lactate, pH and total CO_2-content of arterial blood in recovery from performance of 1500 kg-m in one minute.

The results of the 1500 kg-m. experiments are shown in fig. 40. No significant blood changes were found for 500 kg-m. in one minute. Bicycling 1000 and 1500 kg-m. led to a temporary reduction of pH. The observed changes in total amount of CO_2 were inconsistent. Due to the small number of experiments undertaken for studying this problem, no sure conclusions concerning the effect of the exercise stress on the arterial CO_2-content can be drawn.

Discussion

The blood lactate concentration after performance of strenuous exhaustive exercise may reach 200 mg % (Aastrand 1952). Average maximal values of 100—140 mg % have been reported (Robinson 1938, Johnson and Brouha 1942, Asmussen et al. 1948).

The peak blood lactate value observed during the recovery period in this study ranged from 20—40 mg %, which must be considered to be only moderate compared to the figures referred to above. How-

ever, this blood lactate concentration resulted in a lowering of the pH. The experiments which led to increased acidity of the blood resulted in an excess CO_2-output and a correspondingly high pulmonary ventilation, as previously discussed. Some of this excess CO_2-output is undoubtedly caused by the increased acidity of the blood, although it may be that in addition unknown anaerobic products poured into the circulation influence the respiratory center via the arterial chemoreceptors. It was interesting to observe that when an excess CO_2-output took place during work and the first part of recovery, a corresponding amount of CO_2 was not retained within a reasonable period of time after the exercise.

The removal of lactic acid from the blood is a slow process and after a downward slope is established during the first part of recovery, is almost an exponential function of time. This observation confirms many reports available in the literature (Hill et al. 1923-4, Margaria et al. 1933, Bang 1936). From the data presented it is seen that the pulmonary ventilation remains at the resting level when blood lactate is still high. This indicates that lactic acid as such and in this small concentration does not influence the amount of pulmonary ventilation. This is in agreement with findings reported by Asmussen and Nielsen (1946).

A close relationship between physical fitness (as based on a clinical judgement) and the blood lactate response to a fixed workload is well demonstrated from the data presented, and is in accord with results reported by several authors (Bang 1936, Crescitelli and Taylor 1944).

Striking differences between young and old subjects were observed in the amount of lactic acid formed during performance of the standard exercise load, this showing the deteriorative effects of aging on the fitness for muscular work.

The factors causing interindividual differences for lactic acid formed during a fixed task have been discussed by several authors (Eskildsen 1945, Karpovich 1953). It appears that the factors to consider are the amount of oxygen stored in the muscles (which is only negligible) and the oxygen supply to the tissue, which in turn depends on the maximal blood flow through the working muscle tissue and the oxygen transportation capacity of the blood.

As the diffusion of lactic acid from the working muscles to the local venous blood has been found to be a rapid process, differences

in diffusibility are probably negligible, and may not be a factor to consider in this connection (Barman et al. 1942).

In addition differences in amount of muscle mass involved by the performance of exercise should be considered. For instance, the single muscle cell in a subject using 10 kg. muscle mass in bicycling the ergometer does less mechanical work and consequently requires less oxygen than the single muscle cell of a subject only able to use 7 kg. muscle mass when doing the same type and same amount of work. Provided the maximal blood flow through the exercised muscle is the same in the two subjects, and provided the oxygen transporting capacity of their blood is the same, the subject with the less muscle mass will have to produce energy by anaerobic processes before the other.

The lag in reaching the maximal value for blood lactate after completion of exercise observed in the old subjects was an interesting finding and indicated a slower blood flow through the exercised limbs.

Summary and conclusions

The blood lactate pre- and postexercise was determined at regular intervals on a limited number of subjects. In addition the pH and total CO_2-content of arterial blood was investigated in a few experiments in order to demonstrate the influence of increased lactic acid content on the anion-cation balance.

The results show briefly:

1. Performance of 500 kg-m. did not increase the blood lactate in young men, while this workload led to an elevation in young women and old men.
2. Performance of 1000 as well as 1500 kg-m. in 1 minute increased the blood lactate in young men.
3. Blood lactate remained elevated for a longer period of time than the O_2-intake and CO_2-output.
4. Peak values for blood lactate were reached 2—5 minutes after cessation of exercise, this time being considerably longer in old subjects.
5. Bicycling 1000 and 1500 kg-m. in one minute by young men led to a temporary reduction of pH.

HEART RATE

The present knowledge of cardiac output during work has recently been reviewed thoroughly by Asmussen and Nielsen (1955).

During the initial stages of exercise the cardiac output increases first rapidly and later gradually, reaching a steady state value at the same time as the O_2-intake levels off at its steady state value. In steady state exercise there exists for each individual an almost linear relationship between heart rate, work performed and metabolic rate.

Relationship between cardiac output and gas exchange during recovery from exercise has not been thoroughly studied. Barman et al. (1942), investigating cardiac output during recovery, found that cardiac output and oxygen intake followed one another very closely. The rate of decrease of pulse rate was slightly slower, that for pulmonary ventilation even slower, and that for blood lactate was found to be the slowest of all.

The heart rate decrease during recovery has been intensively studied due to the simplicity of this determination. It has long been well-established knowledge that large interindividual differences concerning heart rate recovery time exist. In the healthy population a close relationship between physical fitness and the rate of heart rate decrease has been demonstrated. Athletes average lower in recovery time than nonathletes (Cook and Pembrey 1913), females have on average a longer recovery time than males (Metheny et al. 1942), and prolonged recovery is demonstrated in 40-year-old men compared to 20-year-olds (K. L. Andersen 1955). Practicing physical exercise for a longer period of time brings about a quicker heart rate recovery (Brouha and Savage 1945).

Based on this knowledge, numerous work tests have been introduced purporting to measure the functional status of the cardiovascular system.

Workloads usually induced in clinical circles like knee-bending 15—30 times or similar light exercise lasting for one minute or less,

have shown to be of limited value for the purpose of differentiating the circulatory capacity for work of healthy subjects. Johnson et al. (1942) introduced during the last World War the 5-minute exercise test, which has been named the Harvard Fitness Test. Any form of exercise was recommended for use provided it put sufficient stress on the circulatory system by involving large muscle groups and provided it did not demand some unusual skill for its successful performance. Exercise commonly employed in this test consists of stepping up onto and down from a 16-inch high bench, or running on a treadmill inclined 8.6 % with a speed of 7 miles per hour.

The exercise period lasts until the subjects are exhausted, or a maximum 5 minutes, whichever is first. Johnson et al. (1942) demonstrated that the heart rate recovery curve was almost exponential in shape, and found, consequently, that the curve could be satisfactorily traced when knowing three different points on it.

In the present investigation heart rates were recorded simultaneously with the respiratory gas exchange in order to study the relationship. In addition the heart rate recovery time was determined, and the results related to sex, age and degree of physical activity.

Results

Heart rate in the pre- and postexercise period

The heart rate increase brought about by performance of 500 kg-m. in one minute decreases rapidly in the postexercise period, reaching the resting level in all the experiments undertaken, as shown in fig. 41. When higher workloads were used, the heart rate frequently leveled off at higher value in the postexercise period, which is seen in fig. 41, the data below the line for the equal pre- and postexercise heart rate representing these experiments. This elevation of the rate lasted for at least 20—30 minutes after completion of exercise and far beyond the time required for recuperation of the respiratory gas exchange.

Considering the experiments where a workload of 1500 kg-m. in one minute is used it is seen that the subjects with the highest resting heart rates most frequently obtained an elevated heart rate in the postexercise period. Further, elevated heart rate was seen more frequently in women than men. As low heart rate at rest is believed to

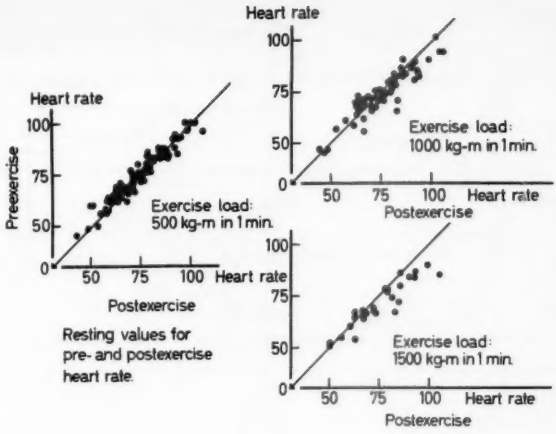

Fig. 41.

Resting values for pre- and postexercise heart rate. Diagonal line confirms with equal values.

correlate with physical fitness, it follows that the prolonged heart rate elevation in the postexercise period is related to physical fitness.

Relation between heart rate and respiratory gas exchange during recovery from brief exercise

Fig. 42 shows data of respiratory gas exchange and heart rate in an experiment where simultaneous recording was made. These experiments illustrate the general trends relating respiration and circulation during recovery from brief muscular exercise.

The heart rate and respiratory gas exchange do not parallel very well. The heart rate recovers long before the CO_2-output reaches resting level. Although determination of the O_2-intake recovery time is inaccurate with the method used, the data available on this topic indicate that the heart rate recovers before the oxygen debt is paid off.

The relationship between CO_2-recovery time and heart rate recovery time is shown in fig. 43. Though a positive correlation exists, this must be considered to be but poor. Consequently, respiratory recovery time cannot be predicted only by considering the heart rate.

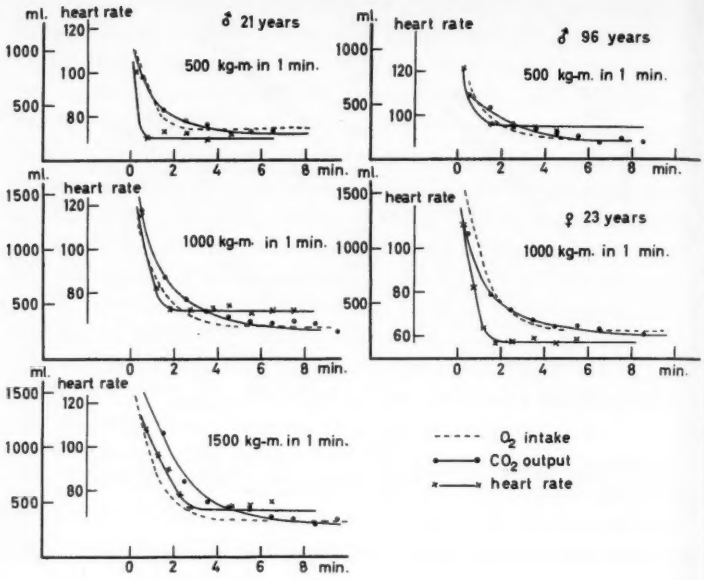

Fig. 42.

The decrease of heart rate, O_2-intake and CO_2-output during recovery from exercise of brief duration. Figure gives data from three subjects. Curves are fitted by eye.

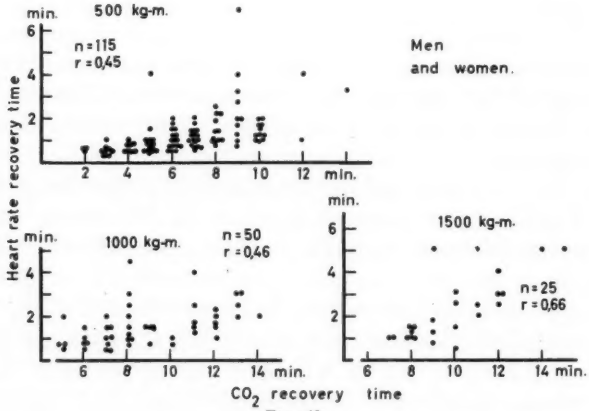

Fig. 43.

Relationship between recovery time for heart rate and CO_2-output.

Age differences

Fig. 44 shows the heart rate response to 500 kg-m. performed in one minute in three male subjects.

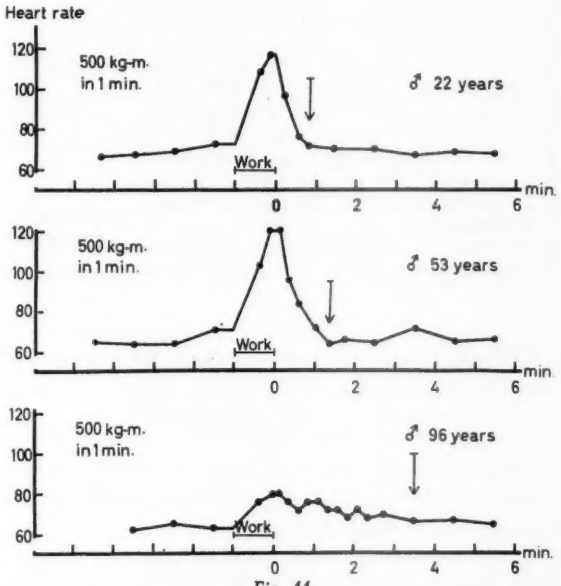

Fig. 44.

Heart rate response to performance of 500 kg-m in one minute.

Some striking differences are demonstrated. In the very old man the heart rate increase is only moderate and the rate of decrease during recovery is slow compared to the younger subjects.

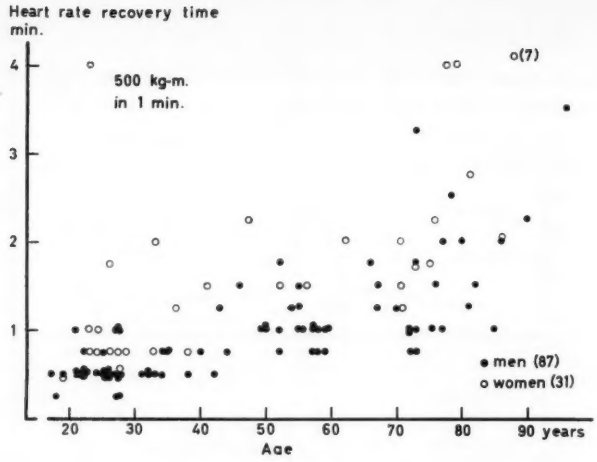

Fig. 45.

Heart rate recovery time in relation to age following performance of 500 kg-m in one minute.

In fig. 45 is plotted the heart rate recovery time against age when experiments using a workload of 500 kg-m. in one minute were conducted, while tables 19 and 20 give the statistical data, the subjects being separated into four age groups.

In fig. 46 are plotted the heart rate recovery time against age in experiments using a workload of 1000 kg-m. in one minute. The results from experiments in which a postexercise heart rate elevated more than 10 % above the preexercise level are disregarded.

Table 19
Recovery time for heart rate (in minutes)
after 500 kg-m. performed in one minute
Men

Age in years	No.	Mean	St.dev.
Below 30	31	0.56	0.20
30—49	15	0.73	0.33
50—69	21	1.11	0.30
70 and above	20	1.61	0.64
Total	87	0.96	0.65

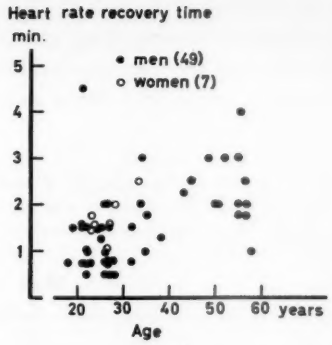

Fig. 46.

Heart rate recovery time following performance of 1000 kg-m in one minute in relation to age.

Sex differences

In fig. 47 the heart rate response to performance of 500 kg-m. in one minute by a young and an old woman is shown, and similar age differences to those demonstrated for men are apparent.

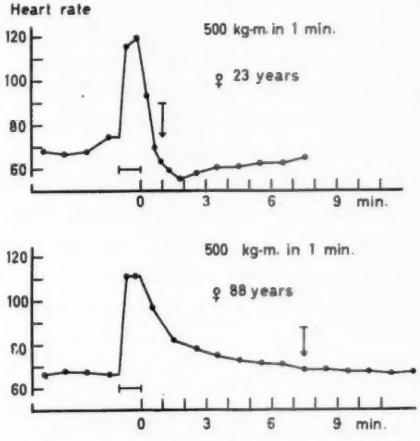

Fig. 47.

Heart rate response to performance of 500 kg-m in one minute.

Table 20 gives statistical data for heart rate recovery time in women. The difference between mean values for all the investigated

men and women below 30 years of age is significant, while the same difference for subjects above 70 years of age only is almost significant. The difference for heart rate recovery time between nonathletes and women below 30 years of age is only almost significant.

Table 20
Recovery time for heart rate (in minutes) after 500 kg-m. performed in one minute
Women

Age in years	No.	Mean	St.dev.
Below 30	11	1.16	1.01
30—49	6	1.42	—
50—69	3	1.67	—
70 and above	11	2.75	1.68
Total	31	1.81	1.84

The effect of physical activity

Fig. 48 shows heart rate response to bicycling 500, 1000 and 1500 kg-m. in one minute. One young champion athlete (bronze medal winner in the 800 meters run during the Olympic Games in 1956) is compared with a nonathlete of corresponding age.

The well-known difference in heart rate at rest and during recovery from exercise in physically conditioned and unconditioned men is clearly demonstrated in the figure.

Table 21 lists statistical data for heart rate recovery times in athletes and nonathletes. The difference between mean values at the 500 kg-m. exercise is almost significant, and the differences at 1000 and 1500 kg-m. are statistically significant.

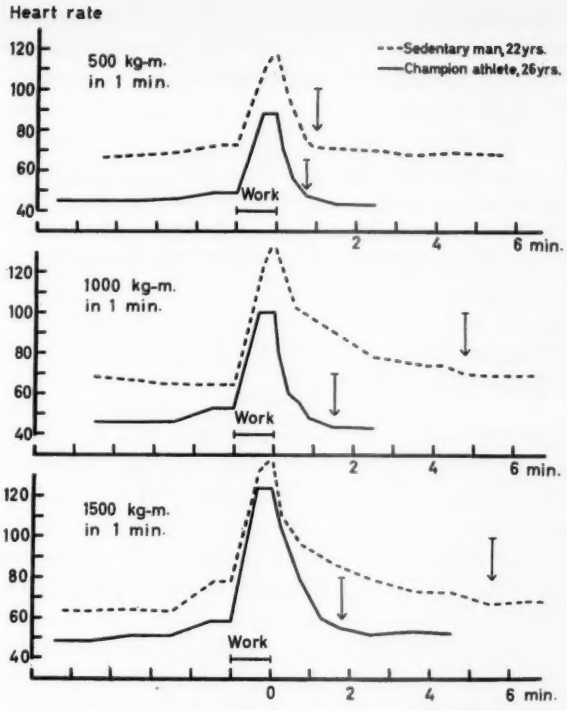

Fig. 48.

Heart rate response to performance of exercise of brief duration in an athlete and a nonathlete.

Table 21

Recovery time for heart rate (in minutes) of athletes and nonathletes

Subjects	500 kg-m.			1000 kg-m.			1500 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.	No.	Mean	St.dev.
Athletes	14	0.46	0.11	11	0.70	0.20	12	1.17	0.36
Nonathl.	18	0.63	0.22	16	1.56	0.88	13 *	3.35	1.32

* includes two subjects with an elevated postexercise heart rate slightly higher than 10 % above the initial level

The elderly physically active men average shorter in heart rate recovery time than elderly sedentary men. However, the difference between mean values is statistically insignificant.

Table 22

Recovery time for heart rate (in minutes) of elderly physically active and elderly sedentary men

Subjects	500 kg-m.			1000 kg-m.		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Active	4	1.00	—	3	2.17	—
Sedentary	11	1.14	0.32	6	2.42	—

Discussion

Several investigators (Grill 1934, Allen et al. 1945) have found that vasodilatation occurs in the muscles following the completion of exercise, and may last for a relatively long period of time. Thus, some amount of blood is pooled in the extremities, reducing the effective circulating blood volume, which in turn is followed by an elevated heart minute volume and consequently an increased heart rate (Herxheimer 1948).

In the present experiments an elevated post-exercise heart rate was found more frequently in unfit than fit subjects, which indicates that the post-exercise vasodilatation lasts for a shorter time or is less pronounced in the latter. The mechanism for this is unknown, and studies directed on this problem would be worth consideration.

In most of the experiments when gas exchange and heart rate were measured simultaneously it was found that the heart rate returned more rapidly to the pre-exercise level than the O_2-intake, CO_2-output and pulmonary ventilation. Except for O_2-intake, this finding confirms observations reported by Barman et al. (1942). They found that O_2-intake recovered earlier than heart rate, and that cardiac output followed the O_2-intake closely. Although the accuracy of the O_2-intake determinations in short time intervals is inadequate by the method used in this study, the data obtained on this problem indicate that the heart rate decrease takes place at a faster rate than the oxygen intake in most of the experiments performed, which thus is in contrast to the experimental results published by Barman et al. They used more strenuous exercise and the

working time was longer. It is suggested that this difference is the cause of the discrepancy.

No determination of cardiac output was undertaken in this study. The heart minute volume is determined by rate and stroke volume. No doubt this varies a good deal, and makes it difficult to predict the level of cardiac output considering heart rate only.

The slower adaption of the heart rate to and the slower recovery from the exercise stress in the older subjects compared with the younger, indicate, however, similar slow adaption and recovery of cardiac output. The heart rate increase during the exercise period is also less in the older subjects, and one can safely predict similar trends in cardiac output. Such differences in cardiac output response to the work stress undoubtedly influence the oxygen supply to the working muscles and the removal of metabolite.

The relatively poor correlation found between recovery time for heart rate and CO_2-output reveals the difficulty of using heart rate recovery time to predict CO_2-recovery time. Whether or not heart rate recovery time is better related to oxygen recovery time is hard to judge from the data collected in this study, as the determination of O_2-recovery time was not sufficiently accurate for this purpose.

Nevertheless, the heart rate recovery time was found to be closely related to the degree of physical fitness, this latter based on a clinical judgement. This finding is in agreement with numerous other reports.

The heart rate recovery time in very old subjects has not, as far as can be seen from the available literature, been studied in the past. The deteriorative effect of aging on the fitness for muscular work is clearly demonstrated in the data presented.

Summary and conclusions

In the present investigation heart rate was recorded simultaneously with the respiratory gas exchange in order to study their relationship. In addition the heart rate recovery time was determined and the results related to sex, age and degree of physical activity.

The results show briefly:

1. In some experiments the heart rate remained elevated for a longer period of time during recovery. In such experiments a determination of heart rate recovery time was difficult to undertake. Evidence was found showing that the prolonged heart

rate elevation in the post-exercise period is related to physical fitness.

2. The decrease of the heart rate and respiratory gas exchange does not parallel very well during recovery from brief exercise. The heart rate recovers long before the CO_2 reaches resting level, and the data also indicate that heart rate recovers before the oxygen debt is paid off.
3. Definite age differences for heart rate response to brief exercise were found. In elderly people the heart rate increase during exercise is only moderate and the rate of decrease after exercise is slow compared to the younger subjects.
4. Heart rate recovery times in women were statistically significantly longer than in men.
5. The well-known differences concerning heart rate at rest and during recovery from exercise in conditioned and unconditioned subjects were confirmed.

BELLOWS FUNCTION OF THE LUNGS

The ventilation as a limiting factor in exercise has been considered by a few investigators (Aastrand 1952, Norris et al 1955). It appears that among young healthy subjects the ventilatory capacity of the lungs is unlikely to be a limiting factor for the physical working capacity.

In this study a higher extra ventilation was found in elderly than young subjects when performing the same amount of work.

In the available literature on the topic (Comroe 1955, Norris et al. 1956) it was found that the bellows function of the lungs was considerably reduced in elderly subjects. The question was raised whether or not the bellows function of the lungs of the old people is so reduced that it becomes a limiting factor in exercise, and studies directed on this problem have therefore been undertaken.

The vital capacity and its subdivisions and the maximal voluntary breathing capacity were measured in all the subjects who performed the work tests. The effect of age, sex and physical training was considered.

Results

Vital capacity and its subdivisions

Fig. 49 gives the vital capacity in relation to sex and age. Sex and age differences are clearly demonstrated in the figure.

A high positive correlation exists between vital capacity and body size as shown by numerous previous investigators, and this relationship exists in the material presented here. Fig. 50 shows the correlation between vital capacity and stature, weight and surface area in subjects below 40 years of age. The highest correlation was found between vital capacity and stature, as several authors have reported previously.

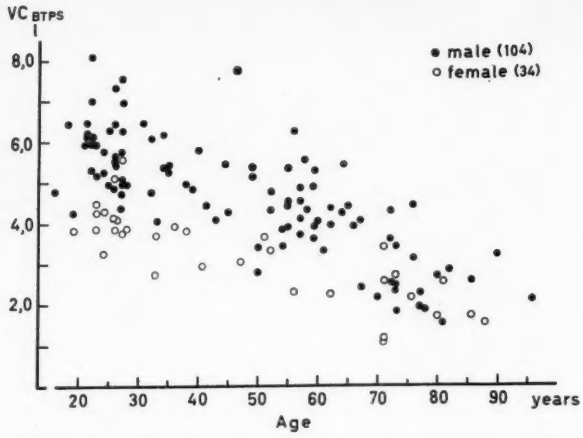

Fig. 49.
Vital capacity (BTPS) in relation to age and sex.

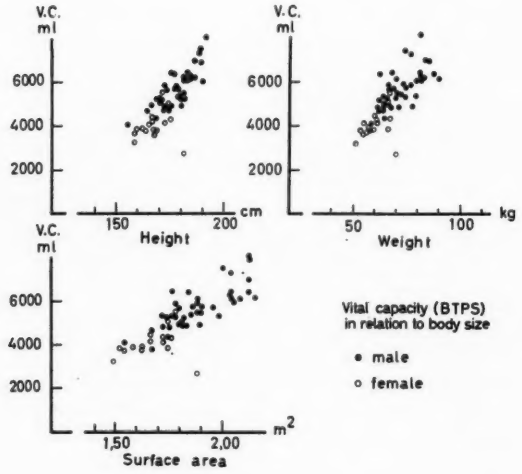

Fig. 50.

Vital capacity (BTPS) in relation to body size.

Table 23

Vital capacity and its subdivisions (volumes in ml. at BTPS)

Men

Age in years	No.	V.C. ml.		V.C./height*		Exp. reserve		Insp. cap.	
		Mean	St.dev.	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.
Below 30	34	5838	904	32.8	4.00	2097	412	3741	610
30—49	19	5371	938	30.5	4.17	1864	556	3506	649
50—69	31	4287	848	24.5	4.47	1223	559	3064	472
70 and over	20	2708	800	16.2	4.58	573	431	2135	655

* = height in cm.

V.C. = Vital capacity
Exp. reserve = Expiratory reserve
Insp. cap. = Inspiratory capacity

Table 24

Vital capacity and its subdivisions (volumes in ml. at BTPS)

Women

Age in years	No.	V.C. ml.		V.C./height*		Exp. reserve		Insp. cap.	
		Mean	St.dev.	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.
Below 30	13	4193	598	25.2	3.22	1455	296	2708	404
30—49	6	3368	—	20.2	—	1102	—	2267	—
50—69	4	2890	—	17.7	—	1020	—	1870	—
70 and over	11	2064	725	13.2	4.62	285	300	1731	265

* = height in cm.

V.C. = Vital capacity
Exp. reserve = Expiratory reserve
Insp. cap. = Inspiratory capacity

In tables 23 and 24 the means and standard deviations of vital capacity and its subdivisions are given, the subjects being separated into four age groups. Concerning the relationship between expiratory reserve and inspiratory capacity it appears that with increasing age the expiratory reserve is reduced relatively more than the inspiratory capacity. Some of the oldest subjects investigated did not have any expiratory reserve at all.

Table 25 gives the means and standard deviations of vital capacity in athletes and nonathletes, and in elderly active and sedentary men.

Table 25
Vital capacity (in ml. at BTPS) of sedentary and physically active men

Subjects	Below 30 years of age			55—69 years of age		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Physically active	14 *	6418	735	13	4700	816
Sedentary	21 **	5480	811	12	4095	757

* = athletes
** = nonathletes

The physically most active men averaged higher. The differences between means are statistically significant in athletes—nonathletes, but insignificant in elderly men.

Maximal voluntary breathing capacity

Fig. 51 shows the maximal breathing capacity in relation to age and sex. Sex and age differences are clearly demonstrated in the figure.

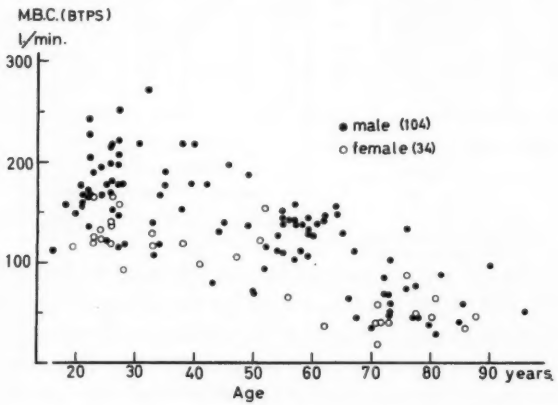

Fig. 51.
Maximal breathing capacity (BTPS) in relation to age and sex.

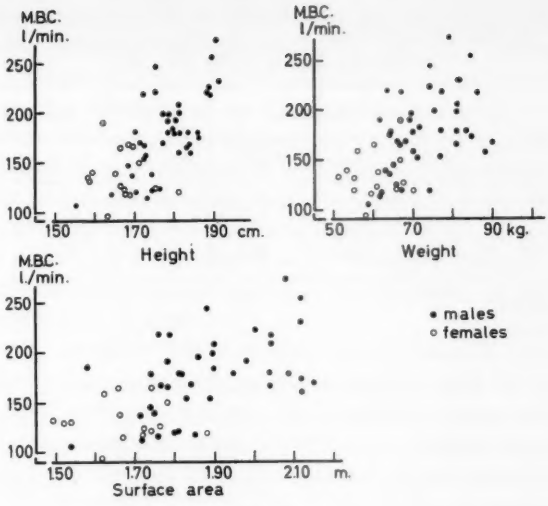

Fig. 52.

Maximal breathing capacity (BTPS) in relation to body size.

Fig. 52 gives the correlation between maximal breathing capacity and body weight, height and surface area. A positive correlation exists between maximal breathing capacity and the parameters used for measuring body size. However, the correlations are apparently lower than they are for vital capacity.

Table 26 gives statistical data for maximal breathing capacity, the subjects being separated into four age groups.

Table 26

Maximal voluntary breathing capacity (liters/min. at BTPS) in relation to age

Age in years	Men			Women		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Below 30	34	176.6	35.5	13	133.6	21.2
30—49	19	168.2	46.5	6	126.8	—
50—69	31	124.0	30.6	4	94.0	—
70 and over	20	64.9	26.9	11	47.5	18.3
Total	104	137.96	54.0	34	99.9	46.0

Table 27
Maximal voluntary breathing capacity (in liters/min at BTPS) of sedentary and physically active men

Subjects	Below 30 years of age			55—69 years of age		
	No.	Mean	St.dev.	No.	Mean	St.dev.
Physically active	14 *	201.1	29.9	13	137.6	13.4
Sedentary	21 **	162.2	30.8	12	117.3	10.8

* = athletes
** = nonathletes

Table 27 gives the means and standard deviations for maximal breathing capacity in athletes and nonathletes, and in elderly active and elderly sedentary men. The physically most active men averaged higher. The differences between means are statistically significant for both groups.

Discussion

Since Hutchinson's classical work on spirometric determination of lung volumes (1846), numerous studies of total lung capacity and vital capacity have been carried out. However, in spite of the voluminous literature on the subject, surprisingly few data are available on the effect of age on the lung volumes. The age studies undertaken are either limited in age range or have very small samples of subjects over 70 years of age. Greifenstein et al. (1952) have tabulated authors' findings on 80 subjects of 47 years and older, who have had various measures of pulmonary functioning. In their own study they found that men over 50 years of age averaged 3.14 l. Birath (1944) determined the vital capacity of 35 males and females aged 18—40 and found average value of 5.08 l. Norris et al. (1956) investigated 135 males ranging in age from 20 to 90 years. Their average figures for vital capacity was 4.84 l. for men between 20 and 30 years of age, and 2.36 l. for men between 80 and 90 years, and a slow but fairly constant reduction was observed during the life span investigated.

The average figures for vital capacity presented in this study are higher than those referred to above, but the age trends are about

the same as found by Norris et al. When discussing this discrepancy one should realize the reliability of the measurement of vital capacity and its subdivisions. This topic has been considered by Georg (1952). He observed a difference of up to 600 ml. by performing the vital capacity test 100 times on the same subject. Consequently, large differences in vital capacity are insignificant. Another factor which markedly may influence the determination of vital capacity is the resistance to the air flow given by the apparatus used for this test, with a tendency to a lowering of the figures as the resistance becomes larger. In the present study the spirometer had only negligible air resistance at air flow below 100 l/min.

However, the higher values for vital capacity found in this study are unlikely to be caused only by poor reliability or by the use of a low resistance apparatus. It is more likely that the differences are due to difference in body size and uneven degree of physical training. That systematic training leads to an increased vital capacity was claimed by Karpovich (1953). This is also evident from the data obtained on athletes in this study.

Sex differences were striking and in accord with several other reports. (Greifenstein et al. 1952, Aastrand 1952.) The differences between means for men and women are statistically significant for all age groups, but only almost significant for subjects above 70 years.

The highest vital capacity recorded in this study was that of a 22-year-old athlete and amounted to 8.08 l. BTPS, the lowest was in a 71-year-old woman and amounted to 1.10 l.

Hermannsen (1933) seems to be the pioneer who introduced the voluntary maximal breathing capacity as a clinical test in order to bring about information of the bellows function of the lungs. Since then this test has been used by several investigators and is now a clinical routine method in many hospitals.

The effects of age on the maximal breathing capacity are considered by a number of authors (Böhme 1938, Hermannsen 1941, Baldwin et al. 1948, Greifenstein et al. 1952, Georg 1952 and Norris et al. 1956). Norris et al. found average values for maximal breathing capacity in men of 20—29 years to be 131 l., while the corresponding figure for men of 80—89 years was 49. A slow but fairly constant reduction took place from the age of 20 to the age of 90. The age trends found in this study are about the same as those referred to above, but the mean values are higher.

Similar arguments to those mentioned for vital capacity may be considered to interpret this discrepancy. In addition it should be stressed that motivation and proper instruction of the subjects are of extreme importance for obtaining maximal values.

Striking sex differences were observed and this is in accord with previous reports (Baldwin et al. 1948, Georg 1952). The differences between means for men and women are statistically significant for all age groups, except for the oldest, which are insignificant.

In the present study physically active men averaged significantly higher in maximal voluntary breathing capacity than sedentary men. This difference may be caused by physical training regimen, which has been shown to improve the maximal breathing capacity in men who trained hard for rowing for six months (Hamre and Jörstad 1955). The finding of a higher maximal breathing capacity in athletes may also partly be attributed to an inherited constitutional physical superiority.

The highest value for maximal breathing capacity recorded was found in a 27-year-old champion athlete and amounted to 253 l (BTPS), the lowest was recorded in a 71-year-old woman and amounted to 18 l.

The bellows function of the lungs as a limiting factor for the fitness for work has been considered in an earlier chapter, page 48.

Summary and conclusions

A higher extra ventilation was found in elderly than in young subjects when performing the same amount of work. The question was raised whether or not the bellows function of the lungs of the old people was so reduced that it became a limiting factor in exercise. In order to study this problem, vital capacity and its subdivisions and the maximal voluntary breathing capacity were measured in all the subjects who performed the work tests.

The results show briefly:

1. Definite age differences were found for vital capacity and maximal breathing capacity. In the age group 20—39 years the mean value of males for vital capacity was found to be 6.55 l., and that for men above 70 years 2.71 l. Similar figures for maximal breathing were 178.0 l. and 64.5 l.
2. Statistically significantly lower values for vital capacity and

maximal breathing capacity were found in females. However, over 70 years of age the difference is insignificant at the 1 % probability level.

3. Athletes have statistically significant higher values for vital capacity and maximal breathing capacity than nonathletes. The same differences were found between elderly physically active and elderly sedentary men in maximal breathing capacity but not in vital capacity.
4. The average figures for vital capacity and maximal breathing capacity found in this study are higher than those reported by other investigators. The reason for this is discussed.
5. The data found for vital capacity and maximal breathing capacity of healthy adults indicate that the bellows function of the lungs is unlikely to be a limiting factor in exercise for the average old person.

GENERAL DISCUSSION

This study of the effect of a standard exercise stress on the respiration and circulation is based on a limited number of selected clinically healthy subjects. In a statistical sense these subjects are by no means representative of the normal population as a whole. This of course limits the generalizations which can be drawn from the data presented. Further, the study undertaken is a vertical cross section rather than a longitudinal and the results obtained demonstrate age differences rather than age changes.

With these reservations in mind we shall discuss the experimental results concerning the physical fitness, this term being defined as the ability for respiration and circulation to recover from a standard workload. Only those trends will be outlined which can be asserted confidently about the striking differences which have been observed.

The respiratory and circulatory recovery times are lowest in subjects between 20 and 30 years of age; the lowest scores appear to be closer to the age of 20 than 30. From the age of 30 years the recovery time increases and from that age and up to about 70 the deterioration in physical fitness seems to take place at a slow but fairly constant rate. Fitness is about halved from the age of 20 to the age of 70. From the age of 70 the reduction in fitness apparently occurs at a faster rate. In the oldest subjects investigated, some above 90 years of age, the fitness was reduced to such an extent that performance of only light exercise led to considerable general discomfort and breathlessness, and required a very long period to obtain complete respiratory and circulatory recovery. As previously emphasized the data indicate that the functional status of the cardiorespiratory system at that age is so poor that a life requiring a higher metabolic rate than only a little above the resting state is out of the question except for a very short period of time.

The deterioration of physical fitness with increasing age is suggested

by common experience. Some studies of age differences for "motor fitness" have also been undertaken by using actual performance events as tests of physical fitness. Definite age differences have been found by a number of investigators (Jokl 1954, Frucht and Boehming 1955, Johansen and Meidell-Sundal 1957). Time used to run 100 m. dash, length of standing broad jump and results of similar athletic exercises have been recorded and related to age. From Norway the most extensive study of "motor fitness" in relation to age has been conducted on seamen's athletic performances (Johansen and Meidell-Sundal 1957). These "motor fitness" studies revealed that maximal scores are obtained in the age between 20 and 30. From the age of 30 a reduction was found to take place at a fairly constant rate down to the age of 50, above which only a very limited number of men have been studied.

The deteriorative effect of aging upon the functioning of respiration and circulation is probably caused by an interaction of several factors. The well-established anatomical aging changes such as sclerosis of blood vessels and reduced elasticity of the connective tissue may be considered first of all in this connection. Although the ill effect of undernutrition and improper diet on the physical fitness is established, the effect on the fitness of different nutritional habits acting over a very long time is unknown. The possible ill effect of long term intensive tobacco smoking should be borne in mind. Environmental stress such as long term exposure to extreme heat and cold should also be considered. As far as these problems are concerned, too little experimental evidence is available to permit any safe conclusion.

Although outdoor recreational habits, involving often extremely hard muscular exercise, are kept up for years by a surprisingly large number of people in Norway, the desire for recreational physical activity in the average person decreases with age. It is probable that the decline in physical fitness can be attributed partly to decreased physical activity. Evidence for this statement is in the finding of a quicker respiratory and circulatory recovery of elderly active compared to elderly sedentary men.

Adult females were found to have a lower degree of physical fitness than males, in agreement with results reported by other investigators (Aastrand 1952). It was interesting to observe that this

difference was reduced in the advanced age groups, and it is doubtful if any sex differences at all exist for subjects above 70 years of age. Several factors may be responsible for the sex difference. It might be that the women's more sedentary life both professionally and recreationally is the whole cause of the longer recovery time. This problem cannot be fully understood in the present state of knowledge.

Within each age group there exists a considerable spread in the experimental data and there may be several reasons for this. The body size is a factor to consider as it was shown that the respiratory and circulatory recovery time as well as the bellows function of the lungs are positively correlated to body weight and height. Another factor is the interindividual differences in mechanical efficiency, which were found to vary a good deal. We know that the degree of physical training varies a good deal within each age group, partly due to differences in type of professional life, partly due to differences in spontaneous physical activity. Although no systematic training study was part of this investigation, it is reasonable to suppose that some of the interindividual differences in fitness for muscular work observed in each age group are brought about by an uneven degree of physical activity. Evidence for this is in the finding of a higher degree of respiratory and circulatory fitness in athletes compared to non-athletes. How uniform a group of subjects having identical records of physical activity in the past would be in their respiratory and circulatory fitness is hard to predict, and experimental data on this question are extremely difficult to obtain on humans.

ABBREVIATIONS

No.	=	number of subjects.
st.dev.	=	standard deviation.
r	=	coefficient of correlation.
R. Q.	=	respiratory quotient.
R. D. line	=	respiratory difference line.
p CO_2	=	CO_2-tension of arterial blood.
V. C.	=	vital capacity.
M. B. C.	=	maximal voluntary breathing capacity.
BTPS	=	body temperature, ambient barometric pressure, saturated with water vapor.
STPD	=	standard temperature and barometric pressure (o C°, 760 mm.Hg), dry.
ATPS	=	ambient temperature and barometric pressure, saturated with water vapor.

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